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Transitions in Science Education: Sustainability and Digital Advances

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About These Proceedings

The Proceedings of ESERA 2025 is an electronic publication of revised and extended papers presented at the ESERA 2025 conference, organised by the University of Copenhagen, Denmark, from 25 to 29 August 2025 under the theme *Transitions in Science Education: Sustainability and Digital Advances*. All papers in the e-Proceedings correspond to communications submitted to, and accepted for, the ESERA 2025 conference. All proposals to the conference went through a double-blind review process, with most proposals receiving two reviews and some receiving three, before being accepted to the conference.

A total of 1436 contributions (including 74 symposia) were accepted and presented at the conference, and 228 papers are included in the ESERA 2025 e-Proceedings. Following the call for e-Proceedings (deadline 31 January), 248 extended papers based on conference presentations were submitted; the final selection reflects those that completed the post-conference editorial review.

The authors were asked to produce updated versions of their papers, taking into account the discussion that took place after their presentation and the suggestions received from other participants at the conference. The e-Proceedings present a comprehensive overview of ongoing studies in science education research in Europe and beyond, and represent the current interests and areas of emphasis in the ESERA community. The e-Proceedings contain twenty Parts representing the papers presented across the 20 Strands of the ESERA 2025 conference. For each part, the proceedings list the Strand description used for the conference as well as the per strand sub-themes.

The strand chairs serving for ESERA 2025 co-edited the corresponding Part for each of strands 1 to 20. All formats of presentation used during the conference – oral presentations, interactive posters, workshops, exploratory seminars, and symposia – were eligible to be submitted to the e-Proceedings. The co-editors reviewed the updated versions of the papers submitted after the conference.

ESERA, the editors, and the co-editors do not necessarily endorse or share the ideas and views presented in, or implied by, the papers included in this book.

Parts of the editorial process associated with the conference were supported by generative artificial intelligence (for example, in the thematic clustering of contributions). Editorial responsibility for the contents of these Proceedings rests with the editors and co-editors.

How To Cite

Citing The E-Proceedings As A Whole

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Contents

The e-Proceedings are organised in twenty Parts corresponding to the conference strands. Each part contains a separate contents page. Readers can navigate first to the Part they are interested in, and from there get an overview of and select papers.

Part	Strand & co-editors	Pages
1	**Learning Science: Conceptual Understanding** *Co-edited by Ana Sofia Afonso (University of Minho, Portugal) & Massimiliano Malgieri (University of Pavia, Italy)*	**1-76**
2	**Learning Science: Cognitive, Affective, Aesthetic, And Social Aspects** *Co-edited by Regina Soobard (University of Tartu, Estonia) & Radu Bogdan Toma (University of Burgos, Spain)*	**77-132**
3	**Science Teaching Processes And Instructional Design** *Co-edited by Italo Testa (University of Naples Federico II, Italy) & Hanna Stammes (Radboud University, Netherlands)*	**133-185**
4	**Digital Resources For Science Teaching And Learning** *Co-edited by Nathalia Helena Azevedo (University of São Paulo, Brazil) & Leticia Garcia-Romano (National University of Córdoba, Argentina)*	**186-350**
5	**Nature Of Science: History, Philosophy And Sociology Of Science** *Co-edited by Georgios Ampatzidis (University of Thessaly, Greece) & Renee Schwartz (Georgia State University, USA)*	**351-417**
6	**Interdisciplinarity And Education** *Co-edited by Laura Branchetti (University of Milan – Statale, Italy) & Argyris Nipyrakis (University of Crete, Greece)*	**418-573**
7	**Discourse And Argumentation In Science Education** *Co-edited by Andri Christodoulou (University of Southampton, UK) & Metin Şardağ (Van Yüzüncü Yıl University, Turkey)*	**574-631**
8	**Scientific Literacy And Socio-scientific Issues** *Co-edited by Isabel María Cruz Lorite (University of Nicosia, Cyprus) & Eliza Rybska (Adam Mickiewicz University, Poland)*	**632-714**
9	**Science Education For Sustainability, Agency And Futures Literacy** *Co-edited by Olivia Levrini (University of Bologna, Italy) & Laura Colucci-Gray (University of Edinburgh, UK)*	**715-871**
10	**Environment, Health And Science Education** *Co-edited by Sarah Haines (Towson University, USA) & Benedikt Heuckmann (University of Münster, Germany)*	**872-981**
11	**Informal, Non-formal And Out-of-school Science Education** *Co-edited by Patricia Patrick (Columbus State University, USA) & Lorenz Kampschulte (Deutsches Museum, Germany)*	**982-1082**
12	**Equity, Diversity And Identity In Science Education** *Co-edited by Wonyong Park (University of Southampton, UK) & Katerina Pia Günter (Umeå University, Sweden)*	**1083-1225**

Part	Strand & co-editors	Pages
13	**Science Curriculum And Educational Policy** *Co-edited by Irene Drymiotou (University of Nicosia, Cyprus) & Marta Romero-Ariza (University of Jaén, Spain)*	**1226-1271**
14	**Evaluation And Assessment In Teaching And Learning** *Co-edited by Regula Grob (University of Teacher Education Lucerne, Switzerland) & Olia Tsivitanidou (Inquirium, Cyprus)*	**1272-1293**
15	**Pre-Service Science Teacher Education** *Co-edited by María Martínez Chico (University of Almería, Spain) & Carla Morais (University of Porto, Portugal)*	**1294-1429**
16	**In-Service Science Teacher Education And Professional Development** *Co-edited by Èlia Tena (Autonomous University of Barcelona, Spain) & Pedro Reis (Universidade de Lisboa, Portugal)*	**1430-1588**
17	**Science Education In Primary And Pre-primary Learning Contexts** *Co-edited by Ange Fitzgerald (Higher Colleges of Technology, UAE) & Federico Corni (Free University of Bolzano, Italy)*	**1589-1676**
18	**Teaching And Learning Science At Middle And Secondary School** *Co-edited by Ilídio André Costa (Porto University, Portugal) & Dury Bayram (Eindhoven University of Technology, Netherlands)*	**1677-1729**
19	**Teaching And Learning Science At The University Level** *Co-edited by Hendra Agustian (University of Copenhagen, Denmark) & May Lee (Maastricht University, Netherlands)*	**1730-1767**
20	**Methods And Methodological Aspects In Science Education Research** *Co-edited by Kason Ka Ching Cheung (The Education University of Hong Kong, China) & Adrienne Traxler (University of Copenhagen, Denmark)*	**1768-1783**

Part1 / Strand 1

Learning Science: Conceptual Understanding

Co-editors: *Massimiliano Malgieri & Ana Sofia Afonso*

Part 1 / Strand 1 Learning Science: Conceptual Understanding

Science learning from a variety of theoretical and methodological perspectives. Includes theories, models, and empirical results on conceptual understanding, conceptual change approaches to learning in science, methodology for investigating students' processes of concept formation and concept use, and strategies to promote conceptual development.

Sub-themes:

1) Conceptual Change and Cognitive Development in Science Learning
2) Methodologies for Investigating Science Learning
3) Strategies and Interventions for Enhancing Science Learning
4) Models and Theories of Science Learning Processes

Contents

Strand 1: Learning Science: Conceptual Understanding 4

Conceptual Understanding Of Natural Selection Among Biology Students In Upper Secondary School And University Level In Norway 6

Material And Embodied Diagramming In Teaching And Learning About Light And Vision ... 13

Improving Students' Conceptual Change In Particulate Nature Of Matter Using Cognitive Conflict Model: Does Cognitive Ability Matter? 24

Understanding Forces In Magnetic And Electric Fields Through Interleaved Practice And Collaboration 32

Exploring Tidal Phenomena: A Focus On Gravitational Dynamics Between Earth And Moon 41

Learning Chemistry Through A Concept Map With Clickable Digital Resources (Hypermedia Map) 51

Learning A Respiratory Model – Undergraduate Understanding Of And Attitudes Toward The Fick Equation 56

Models As Artefacts From The Perspective Of Instrumental Genesis 64

Conceptual And Methodological Distortion In Pseudoscientific Theories: How Do Undergraduate Students Recognise These Problems? 71

ESERA 2025 Copenhagen

Strand 1: Learning Science: Conceptual Understanding

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Introduction

Strand 1: Learning Science – Conceptual Understanding focuses on the processes through which learners build meaningful understanding in science. Key aspects and topics in Strand 1 include research on conceptual change; theories and models of science learning; methodological approaches to investigating the learning process, including diagnostic questionnaires on student conceptions; and strategies, activities, learning progressions which can improve conceptual understanding.

Research on student difficulties and misconceptions has a foundational role in science education, as the attempts at interpreting the widespreadness, robustness and resistance to change of these alternate conceptions originated research on conceptual change, and guided research on productive educational strategies. Within Strand 1, several contributions addressed this issue. Nyléhn and colleagues highlighted that natural selection is a central concept in evolutionary biology, essential for understanding biodiversity. They investigated how understanding of natural selection develops across increasing levels of biology education, from upper secondary school to university. Their findings showed that understanding improves with educational level; however, persistent misconceptions remain common, even among master level biology students. One such misconception is the belief that evolution is goal-directed or intentional, reflecting teleological reasoning. Ferguson, Tytler, and Kamat reported on a design-based research intervention with multimodal characteristics in the teaching and learning of physical optics in Australian upper primary schools. Their study explored how contemporary pragmatist semiotic perspectives can deepen understanding of key conceptual challenges associated with learning about light and vision. The authors observe how students progress across the sequence from ingenuous conceptions of vision (i.e. "rays from the eye", "sea of light", that is light as a facilitator of vision) to a scientific perspective, and argue that students' common-sense understandings of light can serve as a productive starting point for developing more generalized and epistemically powerful scientific conceptions. Ugwuanyi and Ezema, based on Cognitive Dissonance theory, study the effectiveness of cognitive conflict strategies in eliciting conceptual change about the particulate nature of matter in Nigerian secondary school students. They find cognitive conflict strategies to be significantly more effective than the 5Es educational model in the studied samples, confirming and reinforcing other recent research results.

Traditionally, in formal science education topics are taught separately in the form of units, often disconnected one from the other. However, many researchers argue that teaching two or more related topics at the same time may provide students with a better understanding of both, and in addition reinforce students' productive beliefs about the coherence and interconnectedness of science. Berger, Danzglock and Hänze in their study compared the educational outcomes of teaching the motion of charged particles in electric and magnetic fields as two separate blocks,

or as an interleaved joint sequence. They also compared using both these strategies as mainly individual, or mainly collaborative, work. They found that interleaving strategies are particularly effective in collaborative settings, especially when dealing with complex content. Tampakis and Asimopoulos implemented with prospective primary teachers a teaching–learning sequence on the Earth–Moon system which uses the problem of ocean tides as the focal center for promoting understanding of gravity related concepts. Their results showed that participants progressed from fragmented associations involving the Moon and Sun to a more coherent, gravity-based understanding, reducing competing ideas and consolidating related concepts

The development of scientific understanding can be supported through the use of multiple representations, which help students make sense of complex concepts and potentially overcome persistent misconceptions. In this context, Guilares de Aguiar and Miranda Correia examined the effects of students' prior knowledge and the use of digital resources (i.e., clickable concepts within a concept map) on learning outcomes and cognitive load in the topic of electrical conductivity in metals. Their results showed that the inclusion of clickable digital resources enhanced both factual and conceptual knowledge for learners with low and high prior knowledge, without increasing cognitive load, suggesting a no-overload effect.

Among the possible representations of science, mathematical models hold of course a privileged place, and it is worth investigating how students understand them, and what epistemic value they assign to them. Dohn investigated how biology students understand and apply a fundamental mathematical model in respiratory physiology (the Fick equation), as well as their attitudes toward the use of mathematical expressions in the discipline. The results indicated that many students struggled to articulate their understanding of the Fick principle in precise scientific language, and only a few were able to correctly apply its components in their explanations. Additionally, two contrasting attitudes emerged: some students viewed equations as helpful tools for understanding and remembering concepts, while others perceived them primarily as instruments for numerical calculation in exam preparation. Similarly, Pedersen and colleagues explored students' interactions with models by applying the notion of instrumental genesis. In an empirical study with upper secondary biology students using agar blocks as models of cells to investigate diffusion, the authors demonstrated that this perspective provides a valuable framework for understanding how students appropriate models as epistemic artefacts, thereby supporting the development of modelling practices in science learning.

Finally, Lau Damasceno and colleagues examined conceptual and methodological distortions in pseudoscientific theories. Their empirical study with undergraduate students in a Biological Sciences program revealed that students' analyses of pseudoscience tended to focus predominantly on either conceptual or methodological issues, indicating a partial understanding of the nature of scientific reasoning.

Conceptual Understanding Of Natural Selection Among Biology Students In Upper Secondary School And University Level In Norway

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Natural selection is a core concept of evolutionary biology and modern biological science, and understanding the central parts of the science of life is of uttermost importance for the conservation of nature and biodiversity. We have investigated how the understanding of natural selection develops along with increasing educational level in biology, from upper secondary school to university level. We present our results of a survey of the understanding of natural selection where the Conceptual Inventory of Natural Selection (CINS) was answered in full by a total of 201 participants in three populations of biology students (62 students from upper secondary school, 90 first-year university students and 49 master students). Although the overall understanding of natural selection increased with educational level in biology, the misconceptions decreased to highly different degrees. We discuss 1) misconceptions that were relatively rare in all populations, 2) misconceptions that changed profoundly along with educational levels in biology, and 3) the most common misconceptions which were frequent even at master's level in biology. One example will be discussed in detail in each category. Some misconceptions were rather frequent even at master's level in biology, especially that organisms or mutations are intentional or have goals for the evolutionary changes, and that evolution occurs in single organisms and not at population level. Our conclusion is that these misconceptions should be targeted with interventions and further research.

Keywords: Misconceptions, diagnostic tools, learning progression

Introduction

To understand biology is highly important, especially as natural habitats are destroyed, and the number of species declining (Aleknavičiūtė et al., 2023; Edison et al., 2017). Within biology, evolution and natural selection is a central topic that explains other fields, ranging from ecosystems and biodiversity to human health. To understand evolution means to make sense of biology (Dobzhansky, 1973), how life forms have been developed through many millions of years (Darwin, 1859). Within evolutionary biology, natural selection is a central topic that is particularly hard to understand for many students, even at university level (Athanasiou & Mavrikaki, 2014; Gregory, 2009).

Most of the studies of students' understanding for natural selection are conducted in the USA , and there is a lack of studies from Europe (Kuschmierz et al., 2020). Many misconceptions are known in relation to natural selection (Anderson et al., 2002; Athanasiou & Mavrikaki, 2014; Gregory, 2009). The origins might differ, and some of the misconceptions are also found among teachers and in textbooks (Padian, 2013; Tshuma & Sanders, 2015).

Thus, an investigation of how the understanding of natural selection develops along with educational level in Norway is needed, along with the identification of misconceptions that could

hamper this understanding. We have investigated how the understanding of natural selection changes with education in biology (from upper secondary school to master's level at university), both 1) the overall trend in understanding of natural selection, and 2) identified misconceptions about natural selection at the different levels of education.

Methods

We have assessed the understanding of natural selection in three populations of biology students (upper secondary school, first-year university students, master level) with the Conceptual Inventory of Natural Selection (CINS) (Anderson et al., 2002). Altogether 201 participants answered all questions (62 students from four upper secondary schools, 90 first-year university students, and 49 master students in biology).

The inventory contains 20 multiple choice items assessing ten interconnected key concepts in natural selection, each key concept is measured with two items. Summarized from Anderson et al. (2002), the ten key concepts tested in CINS are 1) *variation within a population*, which is necessary for natural selection. The genetic part of this is 2) *variation is inheritable*. This variation ultimately comes from mutations in the germ cells, which is 3) *origins of variation*. Population growth in the absence of limitations is called 4) *biotic potential*. In the real world, populations are usually relatively stable around the carrying capacity, called 5) *population stability*. This is commonly a result of 6) *limited natural resources*, causing 7) *limitations in survival*. When limitations in survival are combined with individual variation, the result is 8) *differential survival*. Given time, this will be seen as 9) *changes within a population*; and ultimately, given isolation and evolutionary time, the 10) *origin of species*.

The distractors in CINS target widespread documented misconceptions, for instance 1) *evolution has a goal or fulfills a need*, 2) *the use or lack of use of organs has a direct effect on evolution*, and 3) *fitness equal physical strength*. Altogether 24 misconceptions documented in literature are tested in CINS (Anderson et al., 2002).

Analyses of textbooks in Norwegian schools, both in science and biology, were also undertaken. The contents in all parts relevant for evolutionary biology were analysed. In Norway biology is first taught as a separate topic in upper secondary school, prior education in biology is integrated with chemistry, physics and geology and taught as integrated natural science.

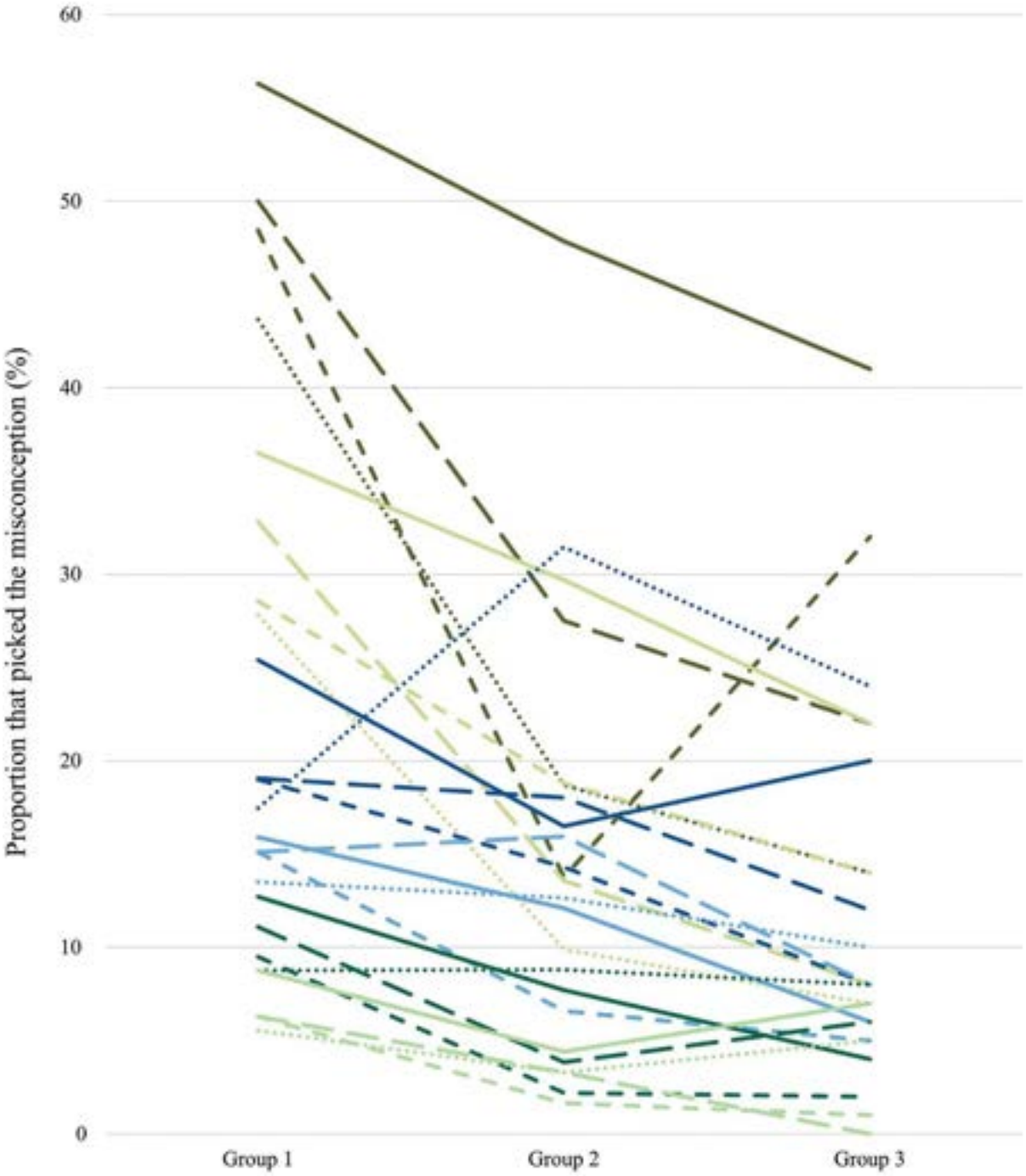
Results And Discussion

Overall, a trend of increasing understanding of natural selection along with educational level in biology was found. There was a rather abrupt and significant change from upper secondary school to first-year students at the university. The maximum score on CINS is 20. The students in upper secondary school had a median of 9 correct answers, while the first-year students scored 13 and the master students scored 14. A small subgroup of master students that have taken an advanced course in evolutionary biology scored, on average,17 correct answers.

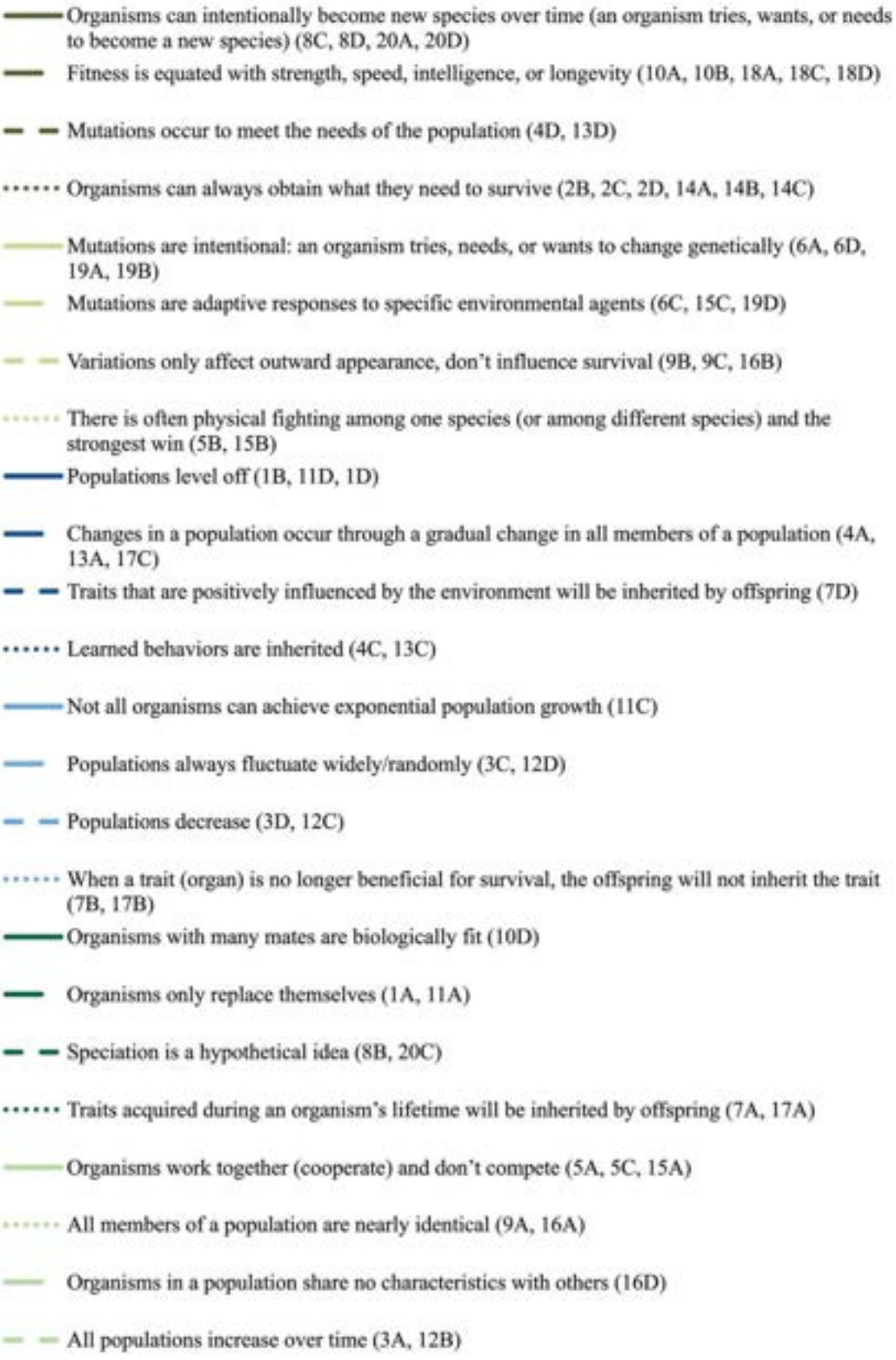
We performed a systematic search for studies that have applied CINS. Comparing all result from studies on CINS, including the results from our study, we found a general trend of lower scores reported in upper secondary school (Lucero & Petrosino, 2017) than among first-year students (Pinxten et al., 2020) with some further increase to master level (Athanasiou & Mavrikaki, 2014). Thus, the overall trend is an increased understanding for natural selection along with education in biology.

Figure 1. Changes in misconceptions from upper secondary school (group 1) to first-year university students in biology (group 2) to master's level in biology (group 3). The misconceptions are sorted according to how frequently they appear in upper secondary school (group 1), if similar, they are sorted according to their frequency in the university populations. A) line diagrams (on next page), B) legends (page following line diagrams).

A) Line diagrams of changes in misconceptions



B) Legends. This is a list of the 24 misconceptions tested with CINS. The uppermost are the most common in the present study, the lowermost are the rare misconceptions. The numbers refer to the items, the letters to the distractors, after Anderson et al. (2002).



Furthermore, altogether 23 of the 24 misconceptions tested in CINS decreased along with educational level in our study (Figure 1). However, the misconceptions decreased to highly different degrees, and some of them were frequently found even at master's level in biology. We will first discuss 1) misconceptions that were relatively rare in all populations, then 2) misconceptions that changed profoundly along with educational levels in biology, before we turn to 3) the most common misconceptions which were frequent even at master's level in biology. One example will be discussed in detail in each category.

Relatively Rare Misconceptions

Half of the misconceptions were relatively rare in all the populations we investigated. One example is the misconception that the use and lack of use of organs resulted directly in evolution (Lamarckism). The relatively rare misconceptions might have been found at a higher frequency if we had applied other diagnostic tools than CINS. In a comparison of three methods of investigation (CINS, the open response instrument ORI, and oral interviews), Nehm and Schonfeld (2008) found that the identification of misconceptions depended on the method of investigation. For instance, they reported that Lamarckism was the most common misconception identified with ORI and oral interviews but ranked as the 12th most common based on CINS. Thus, although low scores were obtained for these misconceptions on CINS, they could have been more prevalent using other measurements.

We have compared our results with the other studies we found that report scores for the misconceptions targeted with CINS – Australian 10th graders, (McLure et al., 2020), undergraduate biology majors in USA (Nehm & Schonfeld, 2008) and undergraduate students in Belgium and The Netherlands (Pinxten et al., 2020). Overall, the most frequent misconceptions in our study were also the most prevalent in these studies. This supports that the instrument is crucial in the identification of misconceptions.

In our analysis of school textbooks, we found that some of the rare misconceptions were explicitly targeted. For instance, Lamarckism was frequently explained as a misconception. Such explicit targeting could also have reduced these misconceptions (Gregory, 2009). Such explicit targeting was not found for the misconceptions that were frequent even at master's level in biology.

Misconceptions That Changed Profoundly With Biology Education

Some of the investigated misconceptions changed profoundly from upper secondary school to university level in biology. One example is that fitness equals physical strength, which was found among half the respondents in secondary school in our study, but only 22% of the master students. This misconception is also reported as common in other studies that have applied CINS (McLure et al., 2020; Nehm & Schonfeld, 2008; Pinxten et al., 2020). The term 'fitness' means physical strength outside biology (Gregory, 2009). Such multiple meaning of concepts is known to be problematic and has been discussed in science didactics for decades (Reydon, 2021). Thus, many teachers are probably aware of this and might possibly counteract this misconception through teaching.

Overall, the misconceptions that are changing along with educational level could indicate that education works. On the other hand, there might be some underlying differences between our populations. Especially, only a minority of the students in upper secondary school continue with biology at university level, which might have influenced the measured changes.

The Most Frequently Found Misconceptions

Some misconceptions were frequently found even at master's level in biology. One example is teleological reasoning, that evolution is goal-driven or intentional, for instance that mutations do not happen by chance but are induced to solve a need for the organism. Such misconceptions are frequently found in other studies as well (McLure et al., 2020; Nehm & Schonfeld, 2008; Pinxten et al., 2020). However, teleological reasoning has many forms and some of them might be scientifically correct (González Galli et al., 2020).

Thus, we have also undertaken a more fine-grained analysis of the teleological distractors, based on the classification by González Galli et al. (2020). In our study, the distractor including "need to adapt" was frequently chosen, while few students chose that "the lizards wanted to become different in size, so beneficial new traits gradually appeared in the population". None of the students at master's level chose the latter distractor. Thus, the "worst cases" of teleological reasoning were rare and decreasing with education in biology.

Conclusions And Further Studies

Although there is a trend of increased understanding for natural selection along with educational level in biology, there are also highly frequent misconceptions in all investigated populations, even at master's level in biology at university. Thus, we conclude that more explicit targeting of misconceptions on multiple levels of biology studies, as well as more research, are needed.

Specifically, we have planned a follow-up study with explicit targeting of misconceptions. We have also modified two items in the CINS questionnaire for our further use (item 4 and 13, where the distractors "successful behaviors learned by finches/guppies are passed on to offspring" are changed to "successful behaviors learned by finches/guppies are passed on genetically to offspring"). The change is made to specify for the students that genetical changes, and not learning, are meant. Furthermore, we will add other measurements of misconceptions than CINS, for instance interviews of students where they can explain their reasoning verbally.

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ESERA 2025 Copenhagen

Material And Embodied Diagramming In Teaching And Learning About Light And Vision

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In this paper, we report on a design-based research intervention in teaching and learning physical optics in upper primary school in Australia, exploring ways in which contemporary pragmatist semiotic perspectives can advance understandings of the significant conceptual issues identified with learning about light and vision. We collaborated with a teacher to design and refine a Year 6 optics learning sequence. We traced the orchestration of material, embodied, and textual/pictorial representational work involved in students 'diagramming' to investigate and explain reflection phenomena and identified challenges students faced in coordinating their common-sense reasoning with the abstract explanatory systems of science. We use Peirce's sign function categories – iconic, indexical, and symbolic – to interpret the nature of this transduction work that leads from immediate personal diagramming experiences to 3D and 2D abstracted diagramming that constitutes the semiotic ecology underpinning canonical scientific optical concepts and practices. We argue that the science classroom ought to welcome students' common-sense understandings of light as the starting point for developing an appreciation for the potentially more epistemically powerful, generalised scientific understandings of light, with students maintaining this common-sense reasoning embedded in practical purposes.

Keywords: material-embodied, optics, reasoning

Introduction

The relationship between light and vision, the study of optics, is an important topic in general science and in physics curricula. This relates to the visual nature of our interaction with the world, and the relevance of optics to explain natural world phenomena and optics-based technologies. Research in the student conceptions area, since the 1980s, has established difficulties for students in recognising light as a tangible entity that travels (Galili, 1996; Guesne, 1985). Several alternative student conceptions of light have long been recognised, including ideas of: 1) light as illuminating objects with the process of vision seen as unproblematic, 2) light as an effect on surfaces or associated with light sources, and 3) vision interpreted through the construct of active looking (Chu et al., 2009; Shapiro, 1989). Selley (1996a; 1996b) developed an influential phenomenological progression in conceptions leading from a 'sea of light' perspective to an 'active sight' egocentric conception to a 'reception' conception of light as travelling and received by the eye. However, such research has focused on the pathways of change from 'naïve' to scientific conceptions but generally has not articulated the mechanisms by which such shifts occur, beyond recommending explicit attention to setting up the conditions for students to recognise the advantage of scientific ideas (Caravita & Halldén, 1994). Nevertheless, the program of establishing canonical science ideas for interpreting phenomena building from these alternative conceptions remains an important aspect of science teaching and learning (Vosniadou, 2020). In particular, these student conceptions present a challenge for teachers in attuning to students' ideas that may make successful learning more difficult and devising approaches that address this need for a shift in perspective (Paçacı et al., 2024).

More recently, attention has shifted away from a purely cognitivist perspective on student conceptual change (Tytler & Prain, 2013; Lemke, 2004) to consideration of the intimate connection between multimodal languages and learning (Kersting et al., 2024; Nielsen & Yao, 2022), including consideration of students starting their learning of light and vision by carefully observing optical phenomena (Fligauf et al., 2022; Sebald et al., 2022). This phenomenological approach values not just the cognitive but also the embodied and material nature of optical experiences. Part of this phenomenological shift has been a pragmatist semiotic perspective that highlights the multimodal nature of students' conceptions of optics. The challenges presented by conventions associated with the ray diagrams of geometric optics (Xu & Prain et al., 2021) are made apparent by this approach, and it becomes possible to explore students' coordination of visual, material, and embodied modes (Prain & Tytler, 2024; Xu & Ferguson et al., 2021) as students undertake diagramming practices with teacher support using iconic, indexical, and symbolic sign functions (Ferguson et al., 2024).

With this recognition of the fundamental role of multimodality in scientific discovery processes and in learning science - including the centrality of bodily and material aspects to such meaning making (Hetherington, 2024; Wilmes et al., 2024) - an alternative framing of conceptual change phenomena has emerged. This approach challenges the purely conceptual versions of knowing, and frames learning as a process of induction into the discursive practices of science (Nielsen & Yeo; 2022; Lemke, 2004). The implication is that conceptual change should not be viewed simply as a shift in mental models or frameworks, but the development of facility with the discursive tools of science which necessarily involves mind and body in integrated ways (Kersting et al., 2021; Kersting et al., 2024). These are the multimodal representations through which concepts are understood and operationalised in science (Tytler et al., 2013). Concepts in science, from this perspective, are semiotic hybrids. To develop new conceptions is a pragmatic matter of learning to use the associated multimodal representations.

In Victoria, Australia, light is included in the Year 5 and year 6 curriculum, Year 9 curriculum, and the Senior Physics curriculum. In this paper, we expand the pragmatist semiotic approach to explore the ways that this may enable new interpretations to emerge of students' engagement with optical phenomena, and the ways in which teachers can support upper primary students (Year 6) to learn key concepts of light and vision through particular optical practices in a guided inquiry setting.

The research questions are:

1. What multimodal sign constructions and transductions are drawn on in developing students' canonical scientific understandings of optics?
2. What roles do common-sense reasoning and diagramming play in developing students' canonical scientific understandings of optics?

Methods

We used a design-based research (DBR) methodology (Brown, 1992; Plomp, 2013) to work with a specialist science teacher (Maja - pseudonym) to create, implement, and refine successive lessons for a learning sequence on light for Grade 6 students (aged 11). Three classes (approximately 30 students each) from this Australian government primary school participated in a range of optical activities as part of this sequence, including tasks to do with the nature of light

and vision, light travel, and reflection from mirrors, which are the focus of this paper. The sequence utilised a guided inquiry, representation construction pedagogy (Tytler et al., 2023).

We collected video/audio of student and teacher interactions and various representational forms in the science classroom. We also collected student artefacts in the form of paper-based and whiteboard-based diagrams of optical phenomena generated in class, and their responses to a pre-test, post-test, and delayed post-test (3-months later).

We employed a micro-ethnographic (Erickson, 2006) approach to the analysis of video/audio records and student artefacts to investigate the semiotic nature of students' diagramming as they engaged with the optical tasks and activated modelling materials with their bodies. We selected examples (Ferguson et al., 2019) of student diagramming that would offer new insights into the nature of this meaning making of optics as supported by Maja's strategic implementation of particular pedagogical moves. We also coded students' responses to the tests in terms of well-known and established optical perspectives: reception of light, sea of light, line of sight, as well as combinations of these, with remaining responses classified as ambiguous. We similarly analysed students' paper-based and whiteboard-based diagrams of optical phenomena in class.

We used Peirce's (1955[1987]) semiotics to analyse the students' artefacts and test responses in terms of their iconic, indexical, and symbolic nature. Peirce proposes that three distinct sign functions underpin all meaning making; 1) *icon* - signify objects by resembling them structurally; 2) *index* - signify their object through a direct epistemic relationship; and 3) *symbol* - signify their objects by some convention that is arbitrary (i.e., socially/culturally endorsed). Such a semiotic approach makes evident that reasoning in the science classroom is not just multimodal – involving all three sign functions that play out in embodied and materials ways (Kersting et al., 2021) – but also transductive – involving switching between and aligning these different sign functions (Prain & Tytler, 2024).

Peirce (CP 1.54)[1] argues that diagrams as a particular arrangement of sign functions are defined by their iconicity. It is through creating and critiquing diagrams that we can become aware of the structural relationships between different parts of objects or different objects within a system. As we propose in Ferguson et al. (2024), teaching and learning in science must prioritise the iconicity of "diagramming" (p. 13) while still appreciating that in reasoning, icons also invariably have indexical and/or symbolic functions.

We also activate Peirce's (1998 [1905]) pragmatism to frame our analyses in recognising that while the method of science is the form of reasoning most able to afford truthful insights into the reality of the world, this is never at the cost of the primacy of common-sense in our daily being in the world through/as habits. Peirce advocates for the importance of "critical common-sensism" (CP 5.439). We need to balance fallibilism and anti-scepticism if we are to really understand and make a difference in the world, in particular in the context of education that ought to be about fostering students to align such perspectives. The implications for the science classroom are that students' alternative conceptions should not simply be dismissed and identified for replacement by canonical science (Strand, 2005). We seek to make use of Peirce's semiotic pragmatism to outline a framing of the teaching and learning of optics that already always starts with valuing

[1] CP x.y = *Collected Papers of Charles Sanders Peirce (1932, 1935)* volume *x*. paragraph *y*.

students' current understandings as the basis, via diagramming, for developing canonical understandings of science.

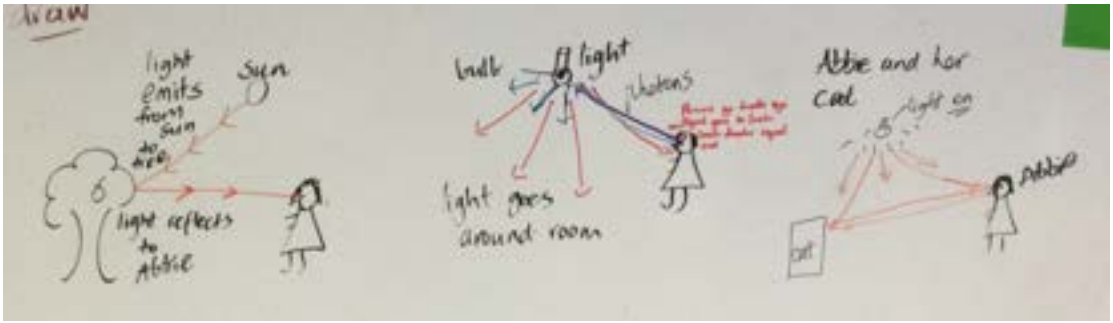
Findings

Across the activities the teacher, Maja, utilised a representation construction approach that encouraged students to represent and share their views about light and vision. Maja moved students towards a consensus around the scientific view - that we see because of reflected light entering our eyes - through presented accounts of vision, supported by small group and whole class review of student generated ideas.

In the first (diagrammatic) activity, designed to probe student ideas about the relationship between light and vision, there were examples in these Grade 6 responses for all four conceptions of light and vision described by Shapiro (1969), with the sea of light conception predominating. However, following the pre-test, Maja showed a video depicting animal eyes adapted to night vision, explaining this in terms of pupil size and photons streaming into the eye and impinging on the retina. Following this, Maja asked students whether the video had changed their understanding of vision. She drew the Sun, tree and Abbie on the board (representing the first question on the pre-test) and asked for a student volunteer to illustrate what was happening. Subsequently she had students construct responses on the board (Figure 1), which she interrogated with the aim of opening up representational alternatives and moving the class towards a consensus around the scientific reception view (through questioning students' assertions, clarifying ambiguities, and occasionally revoicing).

Maja was playing out the pedagogy we had established in previous projects (Tytler et al., 2023); establishing the ray diagram as a productive sign and modelling its use in constructing explanations. This involved a multimodal orchestration with abstracted visual diagramming, verbal language, and gestures. Maja worked with students to establish a need to explain using arrows - indicating direction of light - and the structural relations between the representation using rays and the geometry of the situation. She did not, however, impose the canonical convention as a strict rule. In this discussion, students sometimes referred to 'photons' so that it seemed that the modelling of light as a stream of photons supported students to take a reception view of vision, possibly because this is a material and therefore less abstract representation than that of rays. The breakdown of student conceptions in response to the 'Abbie and the tree' scenario in the pre-test and post-test (at the end of the sequence) is shown in Table 1.

Figure 1: Board work reflecting Maja's negotiation with students for a consensus view of the relation between light and vision.



Change In Conceptions Of Vision Over The Sequence

In the pre-test response to representing the way a girl, Abbie, can see a tree with the Sun in the sky, there was a high incidence of a 'sea of light' perspective by which the tree was illuminated by the Sun and so vision was unproblematic. In a 'line of sight' perspective students privileged the act of 'looking' with arrows from Abbie's eyes to the tree. The third perspective amalgamated this with a reception perspective of light from the tree entering Abbie's eyes, and the fourth, scientific perspective, we called 'reception'. These categories, well recognised in the literature, served to allow a tracking of conceptual changes over the sequence. Table 1 shows a growth in students' views of Abbie and the tree from the pre-test to the post-test.

Table 1: Change in student conceptions of how Abbie sees a tree (percentages).

	Sea of light	Line of Sight	Double perspective	Unclear	Reception
Pre-test (N=32)	44	31	6	3	16
Post-test (N=36)	0	22	11	11	56

The Material And Embodied Dimensions Of Understanding Light And Vision

There is a clear movement of student conceptions across the sequence, particularly away from a sea of light view towards the scientific reception view of vision. The line-of-sight perspective was represented by an arrow from the eye to the object, which we interpret to reflect a focus on the active nature of looking. This was a persistent 'alternative conception' for a quarter of students that we will discuss further, below. The 'combination' perspective arose when students drew arrows, or indicated in text, both light entering the eyes and an arrow from the eyes to the object. We now describe and analyse students' responses to the mirror maze and periscope activity.

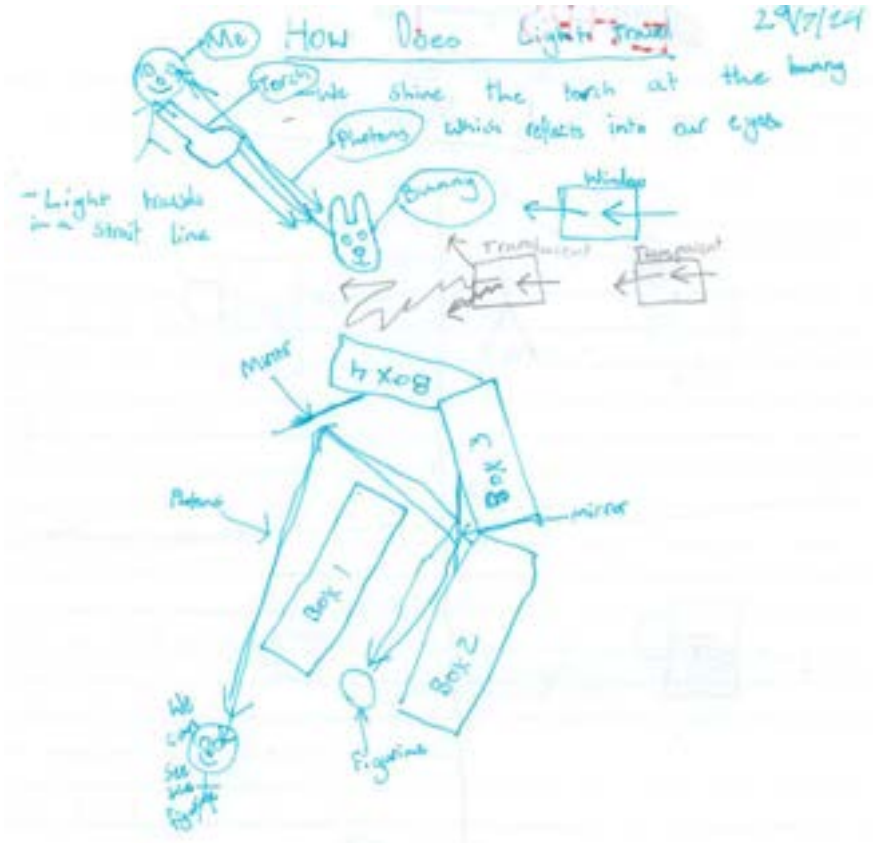
An understanding of the passage of light involving mirrors and images was developed through two activities, in particular: 1) the design of a 'mirror maze' involving students tracing pathways of light from a torch around the maze and subsequently using the mirror positioning to view a small figurine through the maze; and 2) the design and explanation of a periscope. Video of students working on the mirror maze demonstrated the complex material, embodied and visual representation coordination involved in a scientific account of vision using mirrors. In moving around groups constructing their maze and asking, 'what is happening?', students traced the passage of light through the maze with their fingers, combining this with moving their heads in position to emphasise the act of looking back along the light path. This was translated into diagrammatic form that was effectively a birds-eye view of the light path that allowed clear representation of mirror angles and positions needed. The teacher orchestrated groups to enact these multiple embodied perspectives as part of shared interpretation of their experience. Figure 2 and Figure 3 show students indicating with a finger the passage of light, and their subsequent drawing which reflects a scientific reception view.

Figure 2: Student indicating with their finger the passage of light through a mirror maze.



This use of the finger to trace the light path, we refer to as 'diagramming'. Note that the particular path selected is quite strategic; it is one of many paths of light that reflect from the figurine – the student (Ben) understands the figurine to be a source of reflected light and is actively constructing an embodied/visual representation in 3D space to impose an order on what is experienced and interpreted. The diagram he constructs in his book (Figure 3) is a further extension, in more abstracted form, of this embodied diagramming display.

Figure 3: Ben's visual representation of the light pathway through the maze that allows the figurine to be seen.



Note, in Figure 3, the very particular perspective needed – a top-down view- to make apparent the relationship of the mirrors and eye to the light path, and the reference to photons indicative of a reception model of light.

Ben has achieved a coherent account of the pathway of light that explains mirror images, involving: transduction across his 3D embodied diagramming; his visual experience with the torch and mirror images; his verbal descriptions of light paths, images and photons; and then a symbolic, canonical ray diagram. We consider this as the student mastering the semiotic ecology through which students were working with the task, designed by Maja and the research team as particular arrangements through which understandings of the nature of light would be made possible. The arrangement was intended to 'make things visible' in new ways.

For the next activity, students were given broad instructions about the construction of a periscope using cardboard milk cartons, two mirrors and tape, and challenged to design and construct a periscope with which they could see over a wall. Most students successfully constructed a periscope and drew a diagram to indicate how the mirrors allow its use for seeing. We noticed, however, in engaging with students' ideas and practical interpretations of their mirror maze and periscope designs, a flexible movement between arrows representing directions of 'looking' and arrows representing light paths. In talking with students, we found that they would often draw a line-of-sight diagram and present an ambiguous verbal and embodied explanation of the periscope. On questioning ('is that the light direction?') students would often quickly switch their explanation and diagram to a reception perspective, seemingly demonstrating a capacity to flexibly move between the common-sense line-of-sight view and a canonical science view. Two informative examples of researcher-student interactions are given below.

For instance, a discussion took place with Mark who had drawn his arrows coming from the eye into the bottom of the periscope.

> *Researcher: So ... show us how it works?*
>
> Mark picks up the periscope and points his fingers into the bottom, at the mirror.
>
> *Mark: See the light ... comes through.*

In the subsequent discussion, Mark was ambiguous in specifying where to look, where the light entered, and what you are looking at through the periscope. To clarify this, the researcher pushes the point and asks Mark to imagine the periscope is in a submarine as used to look at a ship. Mark sets up his case to represent water with the periscope poking above the water line.

> *Researcher: So where would the light be going?*
>
> *Mark (again pointing through the bottom): Well if I was seeing the light (then points through the top) and I was seeing the thing here ... it goes down (tracing with his hand into the periscope at the top, down the tube and then out the bottom) and into your eyes.*

Other students, similar to Mark, started their representation of how the periscope works using a line-of-sight frame, but on questioning quickly demonstrated that they understood the pathway of light was the opposite, reflecting light from and object into their eyes. In Mark's case, it seemed that the ambiguity of the term 'looking' (where you look from, what you look at) confused his communication. However, his focus on looking in both these senses could be identified as possibly aligned with his line-of-sight diagram, which shows clearly where he looks from, in the periscope, and what he is looking at.

Table 2 shows the post-test results for students' representations of a mirror maze, and periscope. The persistence of the line-of-sight perspective is clear despite a noticeable increase in scientifically accurate views.

Table 2: Student conceptions in explaining the mirror maze and periscope working (in percentage terms).

	Scientifically accurate (reception)	Line of sight	Combination of reception and line of sight	Ambiguous/confused/ missing arrowheads
Mirror maze (N=36)	14	25	22	39
Periscope (N=36)	25	31	11	33

Discussion And Conclusion

This study has confirmed the findings of earlier research in the conceptual change and phenomenological traditions that identifies tensions between everyday (i.e., common-sense) and scientific (i.e. canonical) accounts of light and vision, and the context dependence of these views. However, building on recent research that demonstrates the epistemic power of students' activating their bodies to entangle with the material environment to realise productive science learning (Hetherington, 2024; Wilmes et al., 2024), we offer some fresh insights into student meaning making processes in optics. We draw on Peirce's pragmatist semiotic perspective to consider the complex orchestration of various representations involved, grounded in a semiotic ecology that consists of practical investigative activities, material-embodied interactions, and textual/pictorial abstractions. These processes combine to afford diagramming as a practice of sign making that moves students from common-sense towards canonical explanatory forms, but without ever entirely leaving behind those common-sense insights.

The common-sense line-of-sight account is shown in our analysis to be supportive of students' successful mirror maze and periscope construction using reasoning that accords an active role to 'looking' around barriers and through the instrument, supported by visual alignment of the mirrors to 'see' each other. We found, however, that in prompting students to explain their periscope constructions, that even when their 2D diagramming (textualisions/pictorialisations) and verbal explanations were caste in this common-sense reasoning (grounded in material and embodied 3D reasoning), when asked about 'light' (as opposed to 'vision') they quickly and naturally shifted their perspective to that of a scientific account. The maintenance by almost 30% of students of this common-sense account in the post test we thus consider as not necessarily implying lack of access to the canonical view, but of students not sufficiently valuing this view or recognising that this was the view sought by the test writers. This implies a need to explore ways in which teachers might best support students to recognise both the common-sense and scientific perspectives but embrace the latter as valuable for a wider set of purposes.

We argue that the iconic and indexical functions of students' diagramming play out in different ways, in that these are mediated to different degrees in different semiotic arrangements. Students' embodied and material diagramming was iconically related to their experience of engaging with

the mirror maze and periscope tasks, as they pointed/gestured to indicate the relationship between their eyes, light source, and toy objects (i.e., structural relations) in each case. This diagramming was also immediately indexical in offering a flexible 3D spatial/temporal indicator of the shining of the torch beams. As such, this common-sense diagramming was contextually grounded for students as they tied their reasoning about light and vision to these particular instances of optical events. The students' paper-based and whiteboard-based diagramming, in contrast, is immediately symbolic as evident in the abstracted forms of the 2D arrows (and other 2D elements) of the ray diagrams, symbolically outlining the structural arrangement of optical elements (iconicity) and the explanatory relationships between these elements (indexicality). As such, this more abstracted and precise scientific diagramming potentially made apparent to students the logic of reflection pathways that apply to light and vision in a more generalisable sense. This was achievable through the idealisation of selected light pathways that strip away other possible but non-relevant light paths and lays itself open to inspection and refinement in ways not possible with the embodied and transient 3D diagramming. Students' common-sense diagramming consistent with the line-of-sight view (e.g. pointing at the mirror in which the figurine is seen) needs to be valued for its practical power but also needs to be brought into question in terms of its scientific explanatory power.

In applying our Peircean pragmatist semiotic framing, we suggest that such a canonical perspective makes possible engagement with the periscope and mirror mazes in even more epistemically powerful ways if students can productively relate these to their common-sense understandings of light and vision. In doing so, the less mediated forms of iconicity and indexicality retain a strong presence in meaning making. In this way, we frame vision and light in the science classroom as an opportunity for students to develop the habits of ray diagramming – that is particular ways of activating the body and material environment - through a process of bridging from common-sense diagramming of structural relations to embodied tracing of light paths, which have iconic and indexical relations to the more abstracted 2D canonical forms. In order to understand vision as underpinned by the nature of light, we need to embrace material, embodied, and textual/pictorial reasoning processes. Our science learning sequences should be designed to reflect these multimodal transduction processes, as we embrace Kersting et al.'s (2021; 2024) call for us science educators to radically reimagine teaching and learning science as first and foremost a matter of bodies and materials.

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Improving Students' Conceptual Change In Particulate Nature Of Matter Using Cognitive Conflict Model: Does Cognitive Ability Matter?

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Over the years, Nigerian students' poor performance in Physics has been a major worry to Science Educators, especially those in Physics Education. Some researchers have implicated a lack of conceptual understanding of Physics concepts as one of the major causes of students' poor performance in the subject. However, research is scarce on the conceptual change levels of students with respect to physics concepts especially particular nature of matter. Anchored on cognitive conflict theory, this study adopted a pre-test-post-test non-equivalent control group design. A sample was 195 senior secondary one students SS1 in four intact classes participated in the study. Conceptual Change Test (α = .71) and Test of Logical Thinking (α = .81) were used for data collection. The conceptual change test was used to account for the possible students' naive conceptions (alternative conceptions) on the topics. After the treatment sessions, data collected before and after were analysed using percentage and analysis of covariance. The results showed that the use of cognitive conflict significantly improved the conceptual change of students than the 5E instructional model. It was also revealed that cognitive ability had a significant influence on students' conceptual change in particulate nature of matter. This implies that understanding students' initial levels of conception is very important to teachers and stakeholders for students' sound conception of concepts.

Keywords: Conceptual change, cognitive ability, cognitive conflict

Introduction

In Nigeria, senior high school scientific curricula mandate that all science students take biology, chemistry, and physics in addition to the general courses (mathematics, English language, civic education, and a trade topic) (Oladejo et al., 2023). Due to their substantial contributions to the quality of life in a variety of fields, including healthcare, communication, agriculture, environmental protection, nutrition, transportation, and energy production, science and technology have emerged as critical components of sustainable development on a global scale (United Nations, 2015). However, it has been sadly observed that Scientific literacy, which is essential for scientific advancements, is still low in Nigeria (Oladejo et al., 2023). Specifically, over the years, Nigerian senior secondary school students have consistently performed extremely poorly in physics (Ario, 2024). Reports on pupils' achievement in the West African Senior School Certificate Examination (WASSCE) in physics suggest poor performance of male and female students (Ogbaga et al., 2024). Furthermore, Zudonu et al. (2024) noted that the students' achievement in physics and chemistry which are the major concern of science educators has remained poor over the years as a result of misconceptions and other related factors. According to Madu and Orji (2015), misconceptions are false beliefs or concepts that come from prior information learnt from school or from experiences in daily life. Ideas whose meaning deviates from what is widely acknowledged by scientific consensus are referred to as misconceptions (Cardoso et al., 2020). It was determined that misconceptions are influenced directly by instructor preparation and training as well as student conduct (Guerra-Reyes et al., 2024). Guerra-Reyes et

al. (2024) further found that the primary contributing factors are the consistent use of the didactic transmission-reception model, the impact of students' everyday experiences, the decontextualization of the material being addressed, the inadequate development of research skills, the use of ineffective teaching strategies, texts that are overly formulaic, and exaggerated schemas. In the same vein, Trisniarti et al. (2020) found that assumptions, reasoning, intuition, and associative thinking are frequently the root causes of misconceptions.

In the natural sciences of which Physics is a part, misconceptions can stem from a number of different places. They might result from wrong interpretations of commonplace events, false information obtained from unofficial media sources, or cultural customs. Even in the face of direct, structured instruction, these beliefs become deeply ingrained in students' minds and pose significant obstacles since they are resistant to change. This phenomenon not only makes it difficult to learn new information, but it can also have a negative impact on students' attitudes toward science education by lowering their motivation and level of interest (Guerra-Reyes et al., 2024). The complexity and difficulty of the subject matter (Nugroho, 2021), the kind of instructional materials used, the degree of student engagement (Madaiton et al., 2022), as well as taking into account personal beliefs and prior knowledge (Dorsah & Okyer, 2020), are some of the factors that can affect the development of critical conceptual understanding. These components may play a role in the development of misconceptions, which are personal beliefs and understandings that defy recognized scientific definitions (Blonder & Mamlok-Naaman, 2019). Reconstructing intuitive ideas is necessary to build a more solid scientific conceptual framework in order to gain a thorough knowledge of difficult and contentious scientific concepts (Arabeyyat et al., 2022).

Based on the above, it becomes imperative that science subject especially Physics should be taught using conceptual change models in order to improve students' conceptual understanding. One of the most important objectives of science education, specifically in physics, is to improve students' conceptual understanding of scientific concepts (Laurenty et al., 2021; Wibowo et al., 2017). Therefore, before beginning the learning process, teachers must have a thorough understanding of the preconceptions or assumptions that pupils hold (Samsudin et al., 2024). It has been observed that the impact of cognitive conflict is typically limited, and even after receiving research-based training, students' naive beliefs or misconceptions often continue in some form (Hull & Hopf, 2022). Thus, this research anchoring on the cognitive dissonance theory sought to find out the effect of conceptual change model on students' conceptual understanding of particulate nature of matter.

Theoretical Framework

Cognitive Dissonance Theory By Festinger (1957)

Cognitive conflict model is a part of psychological theories of conceptual change. Festinger (1957) proposed the Cognitive Dissonance Theory (CDT) and suggests that cognitive inconsistency leads to a motivational state that promotes regulation, which comes mainly through a change of opinions or behaviours. Cognitive Dissonance Theory underpins the perception of incompatibility between two cognitions, which can be defined as any element of knowledge, including attitude, emotion, belief, or behaviour. Festinger (1957) opinions that non-fitting relations among cognitions generate a state of discomfort termed dissonance, which is generally

considered as involving negative arousal, that motivates people to cope with this situation, typically by adjusting one cognition to the other.

Festinger (1957) used the term *dissonance* to refer to three different entities: the theory itself, the triggering situation and the generated state. For better understanding, these terminologies can be seen as: the trigger as *inconsistency*, the evoked arousal as *cognitive dissonance state* (CDS) and the theory itself as *cognitive dissonance theory* (CDT). To substantiate the homeostatic nature of dissonance, Festinger drew a connection to hunger: when people are deprived of food, they feel hungry and find ways to cope with it. However, as if the same construct defined food deprivation and hunger, Festinger used the term dissonance for both the triggering relation and the state of discomfort that occurs. Therefore, cognitive dissonance model holds that contradicting cognitions act as a driving force that pushes the learner to acquire new thoughts or beliefs, or to modify existing beliefs, in order to reduce conflict between cognitions.

It is penitent to note that critics have observed that cognitive dissonance theory is subjective and goes with some questions of doubt. Hence, it cannot be objectively measured. This is because individuals function differently. Since what may trigger dissonance in Mr A may not in Mr B. Therefore, most of the issues raised in this theory are linked to cognitive conflict instructional model. This is because in cognitive conflict instructional model, conflicts arising from anomalous situation are resolved before conceptual change will occur. Cognitive conflict instructional model allows students to develop conflict with their own thinking, and it is through this conflict that the students develop their own meanings or at least seek to resolve the conflict. Implementing a cognitive conflict approach has been reported in studies on different concepts such as temperature and heat (Madu & Orji, 2015), acid-base material (Labobar, Setyosari, Degeng & Dasna, 2017), light materials (Wartono, Batlolona & Putirulan, 2018) and courses in computational physics (Akmam et al 2018). Cognitive conflict helps the assimilation process becomes more effective and meaningful in the intellectual formation of learners. It helps learners reflect on explanations of phenomena they learned.

Cognitive Conflict And Conceptual Change

Wartono et al. (2018) found that cognitive conflict strategies can be used to reduce misconceptions that lead to increased student learning achievement. Labobar, Setyosari, Degeng and Dasna (2017) revealed that students had misunderstanding of the concept before, but decreased after treatment with cognitive conflict strategy. Madu and Orji (2015) found that the cognitive-conflict-based physics instruction improved students' conceptual change in heat and temperature over the traditionally designed physics instruction. Orji (2013) revealed that cognitive conflict instruction significantly enhanced students' conceptual change on heat and temperature. In a related research, it has been demonstrated how well students' conceptual mastery was improved by combining the cognitive conflict technique with discovery model physics learning resources (Gunawan et al., 2021). Similarly, it has been revealed that augmented reality with cognitive conflict models significantly improve students' scientific literacy (Mufit & Dhanil, 2024).

From the reviews, none of the studies reviewed investigated the effect of cognitive conflict on students' conceptual change and self-efficacy in particulate nature of matter concepts. It is on this note that the present study sought to investigate the effect of cognitive conflict on students' conceptual change in particulate nature of matter.

Methods

The study adopted a quasi-experimental design; specifically, pre-test-post-test non-equivalent groups design using a sample size of 195 senior secondary one students in four intact classes, in Bwari Area Council of FCT, Abuja. The sample was arrived at using a purposive sampling technique. Particulate Nature of Matter Conceptual Change Test (PNMCCT), and Test of Logical Thinking (TOLT) were used for data collection. The instruments were properly validated by three experts: Two from Physics Education, one from Measurement and Evaluation, all from the Department of Science Education, University of Nigeria. After trial testing, the reliability of PNMCCT was determined to be .71 using Cronbach's Alpha formula, while the reliability of TOLT has been documented by the developers and its reliability was found to be .81 using Cronbach's Alpha method. The reliability index of the three instruments showed that the instruments are reliable.

Ethical approval from the conduct of the research was issued by the Faculty of Education research committee on ethics of the University of Nigeria. Besides, informed consent forms were given to the participants to fill out and sign before the commencement of the treatment. Prior to the administration of the treatments, the students were given PNMCCT and TOLT as pre-test and baseline assessment. The scores from TOLT were analysed and used to categorize the students into different levels of cognitive ability. Two groups of senior secondary one students were exposed to cognitive conflict and 5Es instructional models respectively. The treatment periods which were facilitated by the use of cognitive conflict and 5Es lesson plans lasted for a period of six months. After the treatment sessions, the PNMCCT was administered to both groups of students as post-test. Thereafter, the pre-test and post-test scores were organized and subjected to data analysis. Percentage and analysis of covariance were used for data analysis while the hypotheses were tested at 5% probability levels.

Results

Research Question One: What are the mean conceptual change scores of students taught particulate nature of matter using cognitive conflict instructional model and those taught using 5E instructional model?

Table 1: Mean analysis of conceptual change scores of students taught particulate nature of matter using cognitive conflict instructional model and those taught 5E instructional model.

		Pre-test		Post-test		
Group	**n**	**Mean**	**SD**	**Mean**	**SD**	**Mean gain**
Cognitive Conflict Model	98	33.00	1.34	79.76	2.54	46.76
5E Instructional Model	97	32.45	1.66	71.67	4.65	39.22

It can be seen from Table 1 that students taught particulate nature of matter using cognitive conflict instructional model had a higher post-test conceptual change mean score (M = 79.76, SD = 2.54) than their counterparts taught using 5E instructional model (M = 71.67, SD = 4.65). indicating the efficacy of cognitive conflict.

Table 2: Analysis of covariance of the effect of cognitive conflict instructional model and 5E instructional model on students' conceptual change.

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	321.099[a]	6	53.516	13.960	<.001	.308
Intercept	3630.619	1	3630.619	947.079	<.001	.834
CC Pre Score	4.007	1	4.007	1.045	.308	.006
Instructional Model	100.721	1	100.721	26.274	<.001	.123
Cognitive Ability	140.325	2	70.163	18.303	<.001	.163
Instructional Model * Cognitive Ability	9.010	2	4.505	1.175	.311	.012
Error	720.696	188	3.833			
Total	1161050.000	195				
Corrected Total	1041.795	194				

a. R Squared = .308 (Adjusted R Squared = .286)

Table 2 revealed a significant effect of the cognitive conflict model on students' conceptual change in the particulate nature of matter, $F(1, 188) = 26.274$, $p < .001$.

Table 3: Mean analysis of conceptual change post-test scores of students of different cognitive ability levels.

Cognitive Ability	n	Mean	SD
High	26	76.04	1.32
Average	72	76.00	1.54
Low	97	74.24	2.76

Table 3 shows that students with high cognitive ability had higher mean conceptual change score ($M = 76.04$, $SD = 1.32$), followed by the average cognitive ability students ($M = 76.00$, $SD = 1.54$), and the low cognitive ability students ($M = 74.24$, $SD = 2.76$). Besides, Table 2 revealed that there is a significant influence of cognitive ability on students' conceptual change in particulate nature of matter. Table 2 also revealed that there is no significant interaction effect of instructional model and cognitive ability on students' conceptual change, $F(2, 188) = 1.175$, $p = .311$.

Discussion Of Findings

This research has shown that cognitive conflict model is very effective in improving students' conceptual change in Physics concept like particulate nature of matter. Besides, cognitive ability of the students is a major factor that determine students' conceptual understanding of Physics concept. This result may have been this way because of the instructional relevance of cognitive conflict model. The cognitive conflict model offers an effective framework for teaching that fosters deeper learning and conceptual transformation in a variety of subject areas. The paradigm, which has its roots in constructivist theory, asserts that when students identify inconsistencies between new knowledge and their preexisting mental models, meaningful learning takes place. It thus becomes imperative that Physics teachers should be better positioned to make effective use of cognitive conflict model during the implementation of Physics curriculum.

Buttressing this finding, Wartono et al. (2018) found that cognitive conflict methods can help students learn more effectively by lowering misconceptions. According to Labobar, Setyosari, Degeng, and Dasna (2017), students' conceptual misunderstandings decreased following cognitive conflict strategy treatment. According to Madu and Orji (2015), students' conceptual understanding of heat and temperature was enhanced by cognitive-conflict-based physics training compared to traditionally planned physics instruction. According to Orji (2013), students' conceptual understanding of heat and temperature was much improved via cognitive conflict education. Combining the cognitive conflict strategy with discovery model physics learning resources has been shown to improve students' conceptual mastery in a comparable study (Gunawan et al., 2021). Similarly, it has been revealed that augmented reality with cognitive conflict models significantly improve students' scientific literacy (Mufit & Dhanil, 2024).

More recent studies are in agreement with the finding of this research. For example, It has been found that integrating the cognitive conflict model with the STEM method is advised to enhance students' conceptual knowledge because it may link concepts to practical applications and encourage cognitive reflection through conflict situations (Nabila et al., 2025). Similarly, Research revealed that students' scientific and digital literacy were impacted by the cognitive conflict model-cognitive conflict method combined with mobile learning (Makhrus & Hidayatullah, 2025). According to Makhrus et al. (2025), pupils who were exposed to the cognitive conflict model improved their critical thinking abilities more than those in the control group.

This research has therefore contributed to the field for Physics Education in the Nigerian context through the empirical verification of the effectiveness of cognitive conflict model on students' conceptual change in particulate nature of matter. This is for the fact that no such study has proved that prior to the conduct of this research.

Conclusion And Recommendation

Based on the findings of this research, the researchers concluded that cognitive conflict instructional model is an effective method for enhancing students' conceptual change in particulate nature of matter. Besides, cognitive ability of the students is a major determinant of students' conceptual change when exposed to conceptual change model. It was therefore

recommended that Physics teachers should be better equipped in order to adopt cognitive conflict model in the teaching of Physics concepts.

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Understanding Forces In Magnetic And Electric Fields Through Interleaved Practice And Collaboration

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A method of learning content frequently used in mathematics and science is to first teach one concept in a block and subsequently a second concept in another block. However, several studies have shown this blocked study of one concept at a time to be less effective than intermixing the two concepts in an interleaved study sequence. Yet, Mielicki and Wiley (2022) found that interleaved practice in mathematics was less effective when studying complex concepts. To address the role of complexity in physics education, we adopted the motion of charged particles in electric and magnetic fields as complex physics concepts. In our study 380 students studied this topic in a 2 (blocked vs. interleaved) × 2 (working in dyads vs. individually) - design while playing a serious computer game. As dependent variables we assessed their academic performance in an immediate post-test, as well as a follow-up test 8 weeks later to probe for lasting learning. The analyses revealed no main effects for both problem sequencing and work form in the post-test as well as the follow-up test. However, for both tests, we found a significant interaction that demonstrates the benefits of practicing interleaved problems collaboratively. In conclusion, we conclude that interleaving gains strength in collaborative settings, particularly in learning complex concepts. This result is supported by the concept of the "collective working memory" (Kirschner et al., 2018), which claims that collaborative learning reduces individual cognitive load and fosters subsequent learning.

Keywords: Interleaving, Collaboration, Game-based learning

Introduction

A method of learning content frequently used in mathematics and science instruction is to first teach one concept in a block and subsequently teach a second concept in another block. However, several studies have found this blocked study of one concept at a time to be less effective than intermixing the two concepts in interleaved practice. For example, Ziegler and Stern (2014) report that sixth graders gained a deeper understanding not when the addition and multiplication of variables were presented blocked, but when they were presented interleaved. The students in the interleaved study condition made more errors during training but performed better than students in the blocked study condition on the follow-up tests. From the perspective of cognitive load theory, acquiring conceptual knowledge through interleaved study imposes a higher cognitive load on students, as they must constantly switch between concepts. This switching requires learners to repeatedly retrieve each concept anew, which demands significantly more cognitive effort. However, this repeated retrieval strengthens knowledge structures and ultimately leads to improved learning outcomes. Thus, interleaving can be seen as a form of "desirable difficulty" (as called by Bjork and Bjork, 2011), making the learning process more challenging but more effective in the long term. This effectiveness has been proven in many studies (see the metaanalytic study provided by Brunmair and Richter, 2019).

In this paper two research gaps are addressed. First, the natural sciences of physics, chemistry, and biology are important domains in education at schools and universities. Despite this prominent role of science education, the number of studies on interleaving is small (Richter et al.,

2022). Second, Brunmair and Richter's (2019) meta-analysis shows evidence, in particular, for the effectiveness of interleaving in inductive learning; however, there have been only a few studies to date that deal with interleaved practice with educationally relevant and complex materials. As areas of further research, the authors highlight the need for investigations on educationally more relevant and complex materials, which are underrepresented in existing studies on interleaving.

To address these research gaps, our study focuses on the movement of charged particles in electric and magnetic fields as important concepts in higher physics education. This topic is characterized by its inherent complexity, because students have to deal with multiple theoretical, highly interwoven constructs at the same time, namely force, velocity, and the direction of fields. Furthermore, the deep structural differences between electric and magnetic fields are significant large. Hence, students often confuse electric and magnetic fields (Maloney et al., 2001) and mistakenly apply principles of one field to the other (Scaife & Heckler, 2010; Guisasola, Almudi & Zubimendi, 2004). In addition, because the Lorentz force that governs the charged particles' motion in magnetic fields affects all three dimensions simultaneously, students find it difficult to visualize the relationship between movement, field and forces (Aubrecht & Raduta, 2005; Kustusch, 2016). While interleaved practice could benefit long term learning success, such complexity risks cognitive overload. Mielicki and Wiley (2022) found that interleaved practice was less effective in complex scenarios. Yet, it remains unclear whether the complexity of physics concepts, such as the motion of charged particles in electric and magnetic fields, hinders the effectiveness of interleaved practice.

According to Mullins, Rummel and Spada (2011) students' collaboration is particularly beneficial if the learning material requires elaborative learning activities. From the perspective of cognitive load theory, complex and demanding concepts like the three-finger rule are characterized by high conceptual element interactivity that might hinder learning due to cognitive overload. Kirschner, Sweller, Kirschner & Zambrano (2018) hypothesize that the use of collaborative learning can reduce element interactivity and thus cognitive load. According to the cognitive interdependence principle, appropriate collaborative learning introduces a "collective working memory". That is, various interacting elements can be distributed among the working memories of the different group members, thus reducing cognitive load on a single working memory. In other words, collaboration becomes a scaffold for individuals' knowledge acquisition processes. Furthermore, during collaborative learning, some information comes from other students rather than other sources and that information is likely to become available exactly when it is needed, resulting in a decreased load and increased learning. To evaluate Kirschner et al.'s hypothesis in the present study we examine the role of collaboration and its interplay with interleaving.

Hypotheses

Based on the theoretical background we assume main effects of sequencing and collaboration:

H1: Students working collaboratively on exercises will achieve a higher learning success a) immediately after the learning phase, as well as b) delayed after 8 weeks than students who learned individually.

H2: Students working on exercises in an interleaved sequence will achieve a higher learning success a) immediately after the learning phase, as well as b) delayed after 8 weeks than students who learned in a blocked sequence.

Furthermore, we assume an interaction effect:

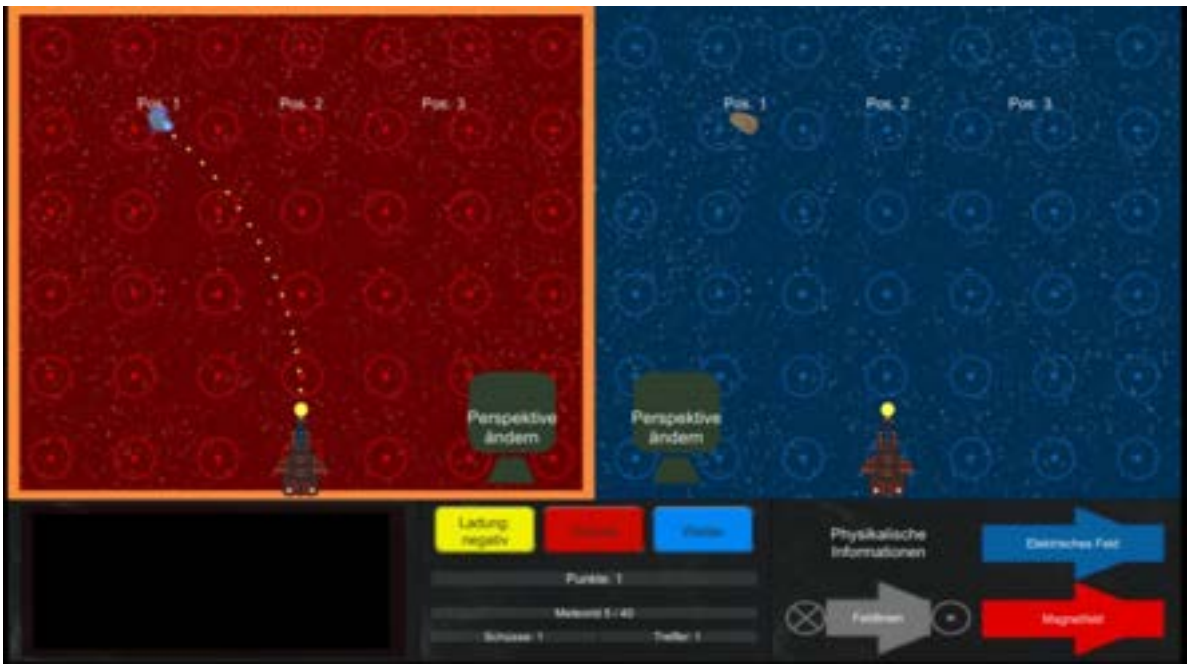
H3: The difference between students who learned collaboratively compared to students who learned individually is greater in the interleaved than in the blocked sequence a) immediately after the learning phase, as well as b) delayed after 8 weeks.

Method

Learning Environment

We have developed a computer-based learning game called “Eraser” (cf. Berger, Kulgemeyer & Lensing, 2019). The objective of the game is to use charged projectiles to shoot down meteorites passing a spacecraft in electric or magnetic fields. “Eraser” is well-suited for simultaneous comparison, because it presents the movement of a charge carrier in a magnetic field on one half of the computer screen and the movement in an electric field shown on the other half of the screen (Figure 1).

Figure 1. Screenshot of the learning game “Eraser”. The active situation is framed in orange. In the interleaved condition, the magnetic field (left) can be compared with the corresponding electric field (right) to detect differences between both concepts.



Participants And Experimental Design

Thirty-one 12th-grade physics classes in the Osnabrück and Kassel regions in Germany with a total of 430 students participated in the study in 2023 and 2024. Prior to the study, students were taught both concepts, the electric and the magnetic field, by their regular teachers. The physics classes were randomly assigned to working in dyads or individually (independent variable “Work form”: collaborative or individually, respectively). In addition, in classes assigned to the collaborative work form the students were randomly paired in dyads. The students in each class were randomly assigned to one of the two conditions (independent variable “Sequence”: blocked or interleaved, respectively). In the data analyses, we considered 380 students with complete data on all variables.

Procedure

The lesson lasted 90 minutes. Students first completed a pre-test (15 minutes). Then, students were introduced to the learning game. During the practice with the learning game in the blocked condition, students saw 18 situations with magnetic fields followed by 18 situations with electric fields. In the interleaved condition, both fields were juxtaposed. In this condition, magnetic fields were on the left and electric fields on the right of the screen. The gameplay lasted 45 minutes. Afterward, students completed a questionnaire on cognitive load and intrinsic motivation, followed by a post-test (20 minutes). About 8 weeks later, they completed another questionnaire on subject interest and a follow-up test to assess learning durability.

Dependent Variables And Scale Analysis

Academic performance

The pre-test encompasses 9 multiple-choice items (magnetic field 4 items, electric field 5 items; cf. Berger et al., 2019). Example items are attached in the appendix. The post-test encompassed the items from the pre-test, and additionally 4 transfer items, covering superimposed electric and magnetic fields. The follow-up test was identical to the post-test. The Cronbach's alpha coefficients were $\alpha = .82$ for the pre-test, $\alpha = .87$ for the post-test, and $\alpha = .89$ for the follow-up test.

Self-report scales

To explore the underlying mechanisms, we assessed intrinsic motivation, cognitive load, and subject interest (as a control variable):

- Intrinsic Motivation: Measured with 3 items (Berger & Hänze, 2009), Cronbach's $\alpha = .77$.
- Cognitive Load: Measured with 2 items (Leppink et al., 2013), Cronbach's $\alpha = .82$.
- Subject Interest: Measured with 4 items based on Horstendahl (1999), covering relevance, positive feelings, and the intrinsic character of interest (Krapp, 2002), Cronbach's $\alpha = .86$.

All self-report scales used 8-point ratings, anchored at "not applicable at all" (1) and "completely applicable" (8). The scales are provided in the appendix.

Results

In order to account for students' interdependence within dyads and within physics classes we ran nested analyses of variance with SPSS Statistics version 27. An example for the SPSS syntax can be found in the appendix. Only students without missing data were taken into account.

Academic Performance

With the pre-test as covariate we got the adjusted means (with standard deviations in brackets) in percent of maximum score for the post-test and the follow-up test as depicted in Table 1.

Table 1. Academic performance (standard deviations) in percent of maximum score for the post-test and the follow-up test with the pre-test as covariate.

Sequence	*Work form*	*n*	*Post-test*	*Follow-up test*
Blocked	Individual	96	51.6 (22.8)	41.6 (26.6)
Blocked	Collaborative	96	53.4 (25.0)	42.4 (27.5)
Interleaved	Individual	93	48.6 (26.0)	35.6 (23.0)
Interleaved	Collaborative	95	59.5 (25.7)	45.6 (29.3)

With regard to the post-test we did not find an effect for sequence (F (1, 213) < 1, p = .49), a marginal effect for work form (F(1, 37) = 3.14, p = .085) and a significant interaction effect (F(1, 211) = 4.21, p = .041), which suggests an advantage for learning collaboratively, especially when students work in the interleaved sequence. With respect to the follow-up test 8 weeks later we found a similar result: There was no effect for sequence (F (1, 352) < 1, p = .50), no effect for work form (F(1, 46) = 1.76, p = .19), but again a significant interaction effect (F(1, 353) = 4.75, p = .030).

Learning Experiences

The means (and standard deviations in brackets) for intrinsic motivation (adjusted with subject interest as covariate) and cognitive load are depicted in Table 2.

Table 2. Learning experiences (standard deviations). Intrinsic motivation is adjusted with subject interest as covariate.

Sequence	*Work form*	*n*	*Intrinsic motivation*	*Cognitive load*
Blocked	Individual	96	5.60 (1.69)	3.70 (1.59)
Blocked	Collaborative	96	5.86 (1.53)	3.82 (1.75)
Interleaved	Individual	93	5.32 (1.70)	3.90 (1.40)
Interleaved	Collaborative	95	5.83 (1.28)	3.08 (1.46)

For intrinsic motivation we found no effect for sequence (F(1, 219) < 1, p = .35), a significant, but small effect for work form (F(1, 33) = 4.17, p = .049, d = .24), and no interaction effect (F(1, 220) < 1, p = .45). For cognitive load we found no significant effect for sequence (F(1, 222) = 2.67, p = .10), no effect for work form (F(1, 37) = 1.78, p = .19), but a significant interaction effect (F(1, 223) = 8.21, p = .005). In particular, during interleaved practice the cognitive load when working in dyads is smaller by Cohen's d = 0.57 compared to individual work.

Discussion

Using the learning game “Eraser” to study the motion of charged particles in electric and magnetic fields, we conducted a study to assess the role of both sequencing (blocked or interleaved) these concepts, and work form (collaborative in dyads or individual) for learning success.

With respect to the variable work form the findings does not provide significant support for hypothesis H1. While there are marginal advantages for collaborative learning in dyads compared to individual work in the post-test, no effect is observed in the follow-up test. Working in dyads is associated with increased intrinsic motivation. Therefore, the learning environment appears to be more suitable for collaborative task engagement, which fosters intrinsic motivation, even though this does not correlate with clear performance benefits in the tests.

With respect to the variable sequencing, we did not find any effect at all, neither for the post-test nor the follow-up test 8 weeks later. Thus, hypotheses H2 is not supported. Several studies attest that interleaving has a stronger positive effect on category learning in comparison to blocking. However, in the present study learners must not only categorize a problem but also adapt the solution procedure to the given type of problem, e.g. to use the three-finger rule for a magnetic field that is perpendicular to the direction of motion. Hence, the problem is demanding due to its inherent complexity. Our results and this interpretation is in accordance with the work of Mielicki and Wiley (2022), who also did not find a benefit of interleaving in the mathematical context of combinatorics, where students must not only be able to accurately categorize problems but also to map these problems to corresponding solution procedures, which must be remembered as well as correctly executed.

However, as expected from hypotheses H3, we found interactions between work form and sequencing in the post-test, as well as in the follow-up test. More precisely, working on interleaved problems collaboratively is most beneficial for learning. The concept of collective working memory (Kirschner et al., 2018) postulates that collaboration can contribute to the fact that a student receives help from their partner exactly when they encounter difficulties in solving a task. For instance, the partners can spur on each other to demonstrate and visualize the complex three-finger rule, which may then result in better anchoring its correct usage in memory. This may have supported recall in the post-test and particularly in the follow-up test. The intensive and active use of the visual representation of the three-finger rule with their hands might also help reduce cognitive load. This interpretation is consistent with our finding of a significantly reduced cognitive load with medium effect size in dyads compared to individual work. To strengthen these interpretations, we are currently analysing the audio recordings of the work done in dyads.

In the present study, we used as learning objectives challenging rules regarding the direction of force on moving charge carriers in electric and magnetic fields. An unanswered question is whether more pronounced differences between interleaving and blocking would arise when practicing even more abstract and comprehensive concepts, such as the distinction between force equilibrium on one object and interaction between two objects as described by Newton's laws. In the case of these topics, the assignment of different examples to the two concepts is significantly less clear than in the case of electric and magnetic fields. It is challenging to categorize the problems concerning force equilibrium and interaction law. If, in such cases, both the categorization and the choice of an appropriate problem-solving strategy are challenging, the

interleaving may then show its particular strength in emphasizing the differences between different concepts to a greater extent (Rohrer, Dedrick, Hartwig & Cheung, 2019).

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Appendix

Self-Report Scales

Intrinsic motivation

- The work was really fun.
- I did not notice how the time flew by.
- The topic makes sense to me.

Cognitive load

- The topic covered in the activity was very complex.
- The activity covered concepts that I perceived as very complex.

Subject interest

- I enjoy physics lessons.
- I look forward to the physics lessons.
- Physics is a subject that is important to me.
- I also think about certain topics in physics lessons in my free time.

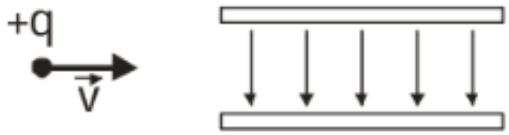
Example SPSS Syntax For The Nested Two Factorial Design

```
MIXED post-test BY sequence workform WITH pre-test
 /FIXED = pre-test sequence workform  sequence*workform
 /RANDOM = INTERCEPT  | SUBJECT(class)
 /RANDOM = INTERCEPT  | SUBJECT (class*dyad).
```

Example Items From The Tests

Task 3

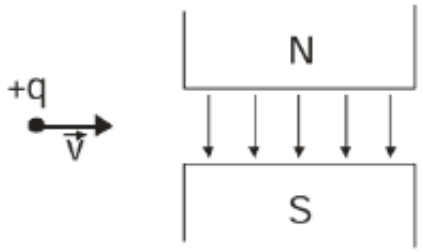
a) The figure shows a positive charge q approaching a homogeneous electric field between the plates of a capacitor at a constant speed $\vec{v}$.



How does the positive charge move after entering the electric field?

❑	It is deflected upwards.
❑	It is deflected downwards.
❑	It is deflected into the paper plane.
❑	It is deflected out of the paper plane.
❑	It continues to move without deflection.

b) The figure shows a positive charge q approaching a homogeneous magnetic field between the poles of a magnet at a constant speed $\vec{v}$.



How does the positive charge move after entering the magnetic field?

❑	It is deflected upwards.
❑	It is deflected downwards.
❑	It is deflected into the paper plane.
❑	It is deflected out of the paper plane.
❑	It continues to move without deflection.

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Exploring Tidal Phenomena: A Focus On Gravitational Dynamics Between Earth And Moon

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Teaching ocean tides has received limited research attention, despite providing a rich context for introducing key concepts in Astronomy and Physics through modelling, Nature of Science discussions, thought experiments, and multiple representations. The key explanatory mechanism is the gravitational Earth–Moon interaction. Although gravity has been extensively studied in Science Education, its specific role in explaining this mechanism remains underexplored, largely due to associated cognitive challenges. This study reports findings from implementing a gravity-focused teaching–learning sequence on the Earth–Moon system with 16 prospective primary teachers from the University of Thessaly (Greece), aiming to support their development of a well-structured explanation of ocean tides. The results show that participants progressed from fragmented Moon/Sun associations to a gravity-based understanding, reducing competing ideas and consolidating related concepts. These findings suggest tides can function as an effective anchor for modelling and multiple representations.

Keywords: Learning environments, science education, pre-service teacher education

Introduction

Teaching core astronomy concepts is pedagogically important because these ideas connect with students' everyday experiences and can support engagement in scientific inquiry and explanation. However, they are often cognitively demanding, and students frequently rely on intuitive, experience-based explanations that may be internally coherent yet diverge from scientific accounts, particularly when coordination of reference frames and understanding of gravitational interaction in the Earth–Moon system are required (Plummer et al., 2016). Over recent decades, science education research has therefore examined students' ideas and learning progressions, alongside the design of instruction and assessment tools that support conceptual change in astronomy. Across this work, studies repeatedly converge on a relatively stable set of topics, including the shape of the Earth and gravity, the day–night cycle, the causes of the seasons, the phases of the Moon, and foundational ideas about the Solar System and stars (Lelliott & Rollnick, 2010).

Against this backdrop, the present study focuses on tides as a productive context for foregrounding Earth–Moon gravitational interaction and the system's dynamical relations as a central explanatory mechanism. Tides are defined as the periodic rise and fall of sea level, shaped primarily by the gravitational attraction of the Moon (and the Sun) in combination with the dynamics of the Earth–Moon system and the Earth's rotation about its axis. Although the periodic pattern is salient, a mechanistic explanation requires linking ideas from astronomy, Newtonian mechanics, and elements of fluid mechanics.

Despite their relevance and visibility, tides are often not understood in depth. While students commonly associate tides with the Moon, substantial cognitive demands arise when accounting for gravity as an action-at-a-distance and for the Earth–Moon system as a two-body system rotating about a common centre of mass (barycentre). In this respect, the international literature

contains relatively few studies that explicitly exploit the two-body relationship in teaching about tides, with instruction often remaining at a simplified level that constrains opportunities for deeper understanding (Ucar et al., 2011).

More broadly, research has documented persistent alternative conceptions about gravity, including difficulties with action at a distance, treating gravity as an intrinsic property linked to motion, and limited recognition of interactional reciprocity as formalised in Newton's third law. Additional patterns include an "absolute" sense of "down", associations between gravity and the atmosphere, and beliefs that gravity is confined to the Earth rather than operating in space and on other celestial bodies (Baxter, 1989; Ruggiero et al., 1985). These conceptions constitute functional mental models and typically require targeted instructional support to be reorganised. Tides, as a phenomenon arising from lunar gravitational attraction acting on the Earth, offer a context for challenging the view that gravity is bounded by the atmosphere or has a purely local character.

Related difficulties have also been reported regarding the concepts of gravity, weight, and mass. Students may not treat weight as the gravitational force acting on a body, instead separating weight from gravity; weight is sometimes linked to air or atmospheric pressure, treated as a property of objects, and confused with mass, while mass may be conflated with volume (Holding, 1987; Mullet & Gervais, 1990; Ruggiero et al., 1985). Because explaining tides requires distinguishing between the amount of matter (mass) and the gravitational force in a given field (weight/force), the phenomenon can support the consolidation of these distinctions through empirical examples and modelling.

Difficulties are also evident in students' representations of the Earth–Moon system. Many adopt geocentric or hybrid models, attribute incorrect orbital paths to the Moon, or assume that the Moon is visible only at night (Dunlop, 2013; Gulbin & Hakan, 2016). The barycentre concept is particularly challenging: the Moon does not orbit the Earth alone; rather, both bodies orbit their common centre of mass. Without this idea, accounts of tides remain fragmented. The existence of two tidal bulges—at the sublunar point and its antipode—requires attention both to spatial variation (the gradient) of the gravitational field across the Earth and to accelerations associated with rotation about the barycentre.

The present study forms part of a wider research programme that explores the didactic potential of tides for teaching key concepts in astronomy and Newtonian mechanics. It aims to elicit pre-service primary teachers' ideas about the nature of gravity and its relation to weight and mass, as well as core characteristics of a two-body system, with the goal of supporting a more scientifically compatible explanation of the simultaneous formation of two antipodal tidal bulges. The paper presents a teaching–learning sequence structured around the Static Tide Model, incorporating experimentation, thought experiments, and simulations, and reports outcomes in terms of movement from fragmented links towards a more coherent, mechanistic account.

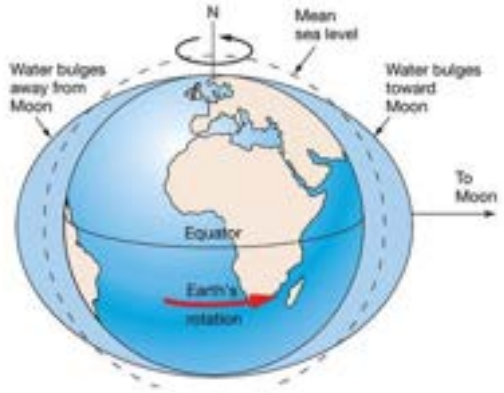
In sum, tides provide a context for connecting concepts that are often taught separately (gravity, motion, reciprocity of forces, two-body systems, barycentre) and for engaging learners through modelling to explain complex phenomena. Given the limited research base on tides within science education (Ucar et al., 2011), this study contributes empirical evidence on how a targeted sequence built around the Static Tide Model can challenge alternative conceptions and strengthen conceptual understanding, positioning tides as a productive phenomenon at the interface of everyday experience and theoretical explanation.

Methodology

The study adopted a qualitative, interpretive design and drew on the teaching experiment methodology (Komorek & Duit, 2014) to trace the development of pre-service teachers' mental models of concepts and phenomena related to gravity and the Earth–Moon system—conceptual resources that are central to explaining tides. The sample comprised eight pairs of third- or fourth-year students from the Department of Primary Education at the University of Thessaly, recruited through convenience sampling. Participants engaged in hands-on tasks, simulations, and structured thought-experiment scenarios intended to support movement from initial, simplified accounts towards more scientifically compatible explanations, with particular emphasis on conceptualising the Earth and the Moon as a two-body system rotating about their common centre of mass (barycentre). Data were collected via written questionnaires, video recordings of the sessions, and observation sheets completed by external observers. The dataset was analysed qualitatively, guided by the trustworthiness criteria of Guba and Lincoln (Lincoln, 2001).

The teaching sequence was designed to support understanding of gravity, the mass–weight distinction, and the dynamical relationship between the Earth and the Moon. It began with elicitation questions (e.g., "What keeps the Earth and the Moon together?") to surface participants' initial ideas and orient discussion towards gravity as an interaction acting at a distance. Participants were then asked to define "force" in terms of observable changes in an object's motion or shape. Next, weight was introduced and explicitly differentiated from mass through practical activities using scales and spring balances. Participants measured mass in kilograms and weight in Newtons and considered that weight can vary across different planets—and, more subtly, across different latitudes on Earth.

Figure 1. Static Tide Model.



Subsequent activities focused on falling-object situations on Earth and on the Moon, together with variants of thought experiments in which the Earth, the Moon, or the Sun is momentarily "stopped". These tasks were intended to foreground that gravity operates throughout space and is implicated not only in the perceived up–down direction but also in motion, including orbital motion. Short video clips of parabolic flights (including ESA material and footage from a small private aircraft) were used to connect the experience of weightlessness to the type of trajectory followed. Participants then explored computer simulations in which gravity could be "switched off", enabling them to observe the resulting changes in the trajectories of satellites and other bodies. To introduce the centre of mass (barycentre) in an embodied way, participants used everyday objects (e.g., a hand axe/hatchet) to identify balance points and relate them to rotation about the centre of mass. Slow-motion video of a thrown hatchet provided a concrete analogue

of rotation about the centre of mass, supporting discussion of barycentric motion in the Earth–Moon system. Additional computer simulations were used to examine further features of this motion, including the relatively stable location of the centre of mass with respect to the Earth. Finally, participants were asked to refine a Static Tide Model (Figure 1) by incorporating the Moon's orbital motion around the Earth, aiming to produce a more coherent and physically grounded account of the phenomenon.

Results

An analysis of participants' ideas about the causes of tides indicates that, although most participants (N=14) recognised the role of the Sun and the Moon, their responses did not articulate a coherent explanatory model—even at a qualitative level—in which gravity is treated as the underlying mechanism (Table 1).

Table 1. Responses regarding the cause of tides.

Responses	Frequencies (N=16)
Associated with the Sun & the Moon	14
• **Magnetic field**	3
• **Gravity**	3
• **Movements**	3
• **Temperature - Sun or Moon**	2
• **Change in density**	1
• **Change in pressure**	1
• **Supernatural force of the Moon**	1
I do not know	2

In addition, although only a small number of participants (N=3) initially referred to gravity as the factor through which the Sun and the Moon generate tides, responses shifted when a more specific question focused exclusively on the Earth–Moon relationship. In this case, the proportion increased, with 13 participants identifying gravity as the primary factor governing the interaction (Table 2). Six of these participants first referred more generally to attractive forces, but later became more specific and explicitly mentioned gravity; two also included magnetic forces as contributing to the Earth–Moon interaction. One participant attributed the interaction solely to magnetic forces, whereas two did not appear to have formed a stable mental model of this relationship. Taken together, differences between responses to the two questions point to the fragmentary and heterogeneous nature of the models in use, even within the same overarching context (i.e., the Earth–Moon–Sun interaction underlying tides).

Table 2. Responses on how the Earth and the Moon interact.

Responses	Frequencies (N=16)
The Earth and the Moon interact through:	
• **Gravity**	11
• **Gravitational and magnetic forces**	2
• **Magnetic forces**	1
• **No response**	2

Regarding the concept of gravity itself (Table 3), all participants correctly recognised gravity as a force, and many described it as attractive (N=11) and acting at a distance (N=7). However, participants struggled to specify between which bodies gravity acts. At the outset, no participant provided an explicit answer to this question. During subsequent discussion with the researcher, the idea began to emerge that gravity operates between all material bodies. The development of a model aligned with the dominant scientific account, however, appeared to be constrained by another alternative idea: for five participants, gases were the only bodies that do not interact gravitationally, possibly reflecting an assumption that "material bodies" include only solids and liquids. In addition, a substantial proportion of participants (N=10) believed that bodies of different mass (e.g., the Earth and the Moon) exert forces of different magnitude on each other. This likely reflects limited appreciation that the gravitational interaction depends on both masses and constitutes a characteristic application of Newton's third law. Overall, although gravity may appear straightforward in its classical description, adequate understanding requires attention to learners' alternative ideas in underpinning concepts, which helps to explain persistent difficulties in teaching and learning it.

Table 3. Reported characteristics of gravity.

Responses		Frequencies (N=16)
Gravity is a force		16
• **attractive**	11	
• **never repulsive**	7	
Acts at a distance		7
Bodies of different mass exert forces of different magnitude		10
Does not act between gaseous bodies		5

Furthermore, analysis of the interview data highlights a localised view of gravity in participants' thinking (Table 4). Gravity was often considered to be active only when one is on a celestial body (primarily the Earth, and within the limits of its atmosphere), while appearing absent in the space

in between. While all participants acknowledged gravity on Earth, this was not the case for the Moon for nearly one third of them. Initially, five participants stated categorically that there is no gravity on the Moon, citing videos of astronauts "floating" or drawing on the idea that gravity exists only where there is an atmosphere.

Table 4. Initial responses on where gravity exists.

Responses		Frequencies (N=16)
Gravity is present everywhere on Earth		16
On the Moon		
Gravity exists		8
No gravity, because:		5
• **Astronauts floating**	3	
• **Lack of atmosphere**	1	
No response		3
In space		
Gravity exists		5
No gravity, because:		11
• **No readings on a scale or spring balance**	7	
• **Astronauts floating**	4	
• **Lack of atmosphere**	1	

Following the teaching episode, however, 12 participants referred to lunar gravity, and six explicitly noted that it is weaker than Earth's. When the discussion turned to the space between the Earth and the Moon, the majority (N=10) initially spoke of an absence of gravity, referring mainly to the lack of readings on a scale or spring balance (N=7), astronauts floating (N=5), and the lack of an atmosphere (N=1). As the episode progressed, participants' views shifted markedly: 14 then stated clearly that gravity exists there as well, and eight suggested that it would be reduced due to increased distance from the Earth or the Moon. These findings underline the influential role of images and videos of astronauts moving on the Moon or in spacecraft orbiting the Earth, which can create an impression of negligible gravitational influence and may contribute to the alternative view that the gravitational field extends only to the limits of Earth's atmosphere.

Additional difficulties were observed in relation to participants' understanding of the direction of the gravitational field. In the thought experiment in which a tunnel passes through the Earth's centre and a ball is released to fall through it, around one quarter of participants produced different predictions depending on whether the tunnel connected the two poles or two diametrically opposite points on the equator. Thus, a ball dropped from the North Pole was expected to exit from the "bottom" of the Earth, whereas if it were dropped from the opposite side of the same tunnel, it would reach the centre and return. In the case of an equatorial tunnel, the ball was

expected to move towards the centre, but with lower speed compared to being released from the North Pole in the other tunnel.

Even greater confusion emerged when participants were asked to describe the ball's motion after it reaches the centre (Table 5). For the majority (N=12), the ball stops there, either because the absence of a "centre" was interpreted as the absence of gravitational force (and therefore of motion and speed), or because all forces were believed to be concentrated there and thus to "hold" the ball stationary. Two alternative ideas are therefore evident: first, that motion without force is impossible (N=4); and second, that the role of the centre of mass of a spherical body as a centre of symmetry within Newtonian mechanics is not recognised. Instead, it is treated as the location where all forces are present (N=3), while its "absence" (because the tunnel passes through it) is taken to imply the absence of gravity (N=8).

Table 5. Initial responses regarding the motion of a ball falling through a tunnel passing through the Earth's centre

Responses		Frequencies (N=16)
The ball comes to rest at the centre because of:		12
• **Absence of forces there**	8	
• **Maximisation of forces**	3	
Depends on latitude		3
Oscillates about the centre		1

Particular difficulties also arose when participants were asked to determine the up–down direction on Earth and in space, since in all responses—at least initially—the criterion used was unclear. For example, when asked to draw where a ball held by people at different locations on Earth would fall, 10 of the 16 did not appear to recognise the role of the Earth's centre: six had difficulty specifying the plane perpendicular to which the ball would fall; two stated that gravity is directed towards the centre but did not represent this in their drawings; and for two others the up–down direction was defined independently of the planet itself, using criteria such as the up–down direction of the page. These findings—possibly reflecting an association between the gravity vector and geographic coordinates or reliance on experiential rules (e.g., "down" defined by the head–feet direction)—indicate the absence of an external, non-egocentric frame of reference, as well as a limited internalised vector model of gravitational force directed towards the planet's centre of mass.

To examine how participants relate gravity to planetary motions, two thought experiments were discussed. In the first, the Earth was assumed to be alone in the universe, moving in some way, and then—hypothetically—stopped for a short period. The question was what would happen next (Table 6). Of the 16 participants, only seven answered that the Earth would remain at rest; five suggested it would continue the same motions as before (with two claiming these motions would be slower), and four argued that it would fall "down". In the second thought experiment, the Moon was assumed to move together with the Earth; both bodies were stopped, and then only the

Earth was released. Based on initial responses, six predicted motions of the Earth towards the Moon; four expected the Earth to continue exactly the same motions as before; three suggested it would remain at rest; and three struggled to provide a prediction. These patterns suggest that many participants did not conceptualise gravitational force as an interaction acting at a distance between material bodies, nor did they understand its role in generating or sustaining the motions of celestial bodies.

Table 6. Initial responses on what the Earth would do as the only celestial body if it were momentarily stopped

Responses		Frequencies (N=16)
Continues its previous motion		5
• **In exactly the same way**	3	
• **More slowly**	2	
Falls 'down'		4
Stops all motion		7

Finally, none of the participants initially recognised that the Moon does not simply orbit the Earth; rather, the Earth–Moon pair, as a system, rotates about their common centre of mass (barycentre), which lies within the Earth. Consistent with the above, participants did not appear to appreciate the role of the Earth–Moon mass ratio in shaping the type of motion the system exhibits. This may reflect one-sided geocentric representations in school science textbooks and limited opportunities for empirical exploration of the reciprocity of gravitational interactions. Moreover, addressing such a complex topic presupposes access to relevant physical concepts or phenomena (such as tides), which remain largely absent from the Greek school curriculum.

Conclusions

The findings indicate that participants recognised the main celestial bodies implicated in tides (the Sun and the Moon), yet they typically lacked a coherent explanatory model in which gravity functions as the organising mechanism. This matters because gravitational interaction is the mechanism that integrates the elements of the phenomenon into a mechanistic account; without it, explanations remain partial. The fragmentary nature of responses—even across closely related questions—suggests the absence of an integrated account of Earth–Moon interaction and, by extension, tides. Instead, participants appeared to draw on loosely connected fragments of personal explanations that were not sufficiently functional for scientific reasoning.

A second key result concerns the sensitivity of responses to problem framing. When asked about the broader Earth–Moon–Sun context, few participants explicitly foregrounded gravity. However, when the focus narrowed to the Earth–Moon relationship, most identified gravity as the primary factor. This pattern suggests that multiple mental models may be available and that their activation depends on contextual cues and task formulation. Alternative ideas also persisted, including attributing the Earth–Moon interaction to magnetism, which can obstruct understanding of why the bodies interact and how tides arise from that interaction.

With respect to gravity itself, most participants described it as an attractive force acting at a distance. Nevertheless, many struggled to specify between which bodies it acts and to generalise the interaction to all material bodies, including gases. A further persistent difficulty concerned Newton's third law and the reciprocal character of interaction. Limited understanding of action–reaction and of the dependence of gravitational force on both masses appeared to underpin the erroneous idea that "the larger body exerts a greater force on the smaller". Such interpretations constrain the construction of a consistent explanatory model and help explain why apparently "simple" classical descriptions of gravity remain difficult to learn.

A particularly salient pattern was the attribution of a "local" character to gravity: it was often treated as operative only on celestial bodies (especially on Earth and within the perceived limits of its atmosphere), while being assumed absent in space. Visual representations—especially images and videos of astronauts floating—seemed to reinforce the idea of "zero gravity" beyond the atmosphere. This underlines the need for explicit teaching to distinguish weightlessness/floatation from the absence of gravity and to explain how orbital motion can produce such experiences despite gravity's presence.

Closely connected to this was difficulty in conceptualising the direction of the gravitational field and the meaning of "up–down". For several participants, direction criteria were egocentric (linked to body orientation or the page's orientation), rather than anchored in an external frame of reference centred on Earth's centre of mass. The absence of an internalised vector model likely contributed to inconsistencies when the reference point changed across the Earth's surface, aligning with difficulties in drawing or reasoning about gravitational direction at different geographic locations.

The thought experiments (a tunnel through the Earth; abrupt "stopping" of the Earth or the Earth–Moon system) surfaced additional alternative ideas. Some participants assumed that gravity becomes zero at the Earth's centre and therefore motion ceases; others assumed that forces are "concentrated" there, holding the ball stationary. These responses indicate uncertainty about the role of the centre of mass and about equilibrium/oscillation around it. Similarly, several participants treated motion as requiring a continuous force, underestimating inertia and the role of initial velocity in the absence of external forces.

Regarding celestial motion, participants often struggled to connect gravity (as an action-at-a-distance interaction) with the generation and maintenance of trajectories. The idea that the Earth–Moon pair rotates about a common centre of mass was largely unfamiliar, and geocentric accounts lacking reciprocity dominated. This appears to reflect a broader difficulty in treating gravitational interaction as a two-body relation with reciprocal consequences, rather than as the one-sided action of a larger body on a smaller one.

The designed teaching–learning sequence aimed to support a gradual shift from simplified, alternative models towards more integrated, scientifically compatible explanations of tides and the underpinning concepts. Through experiments, structured thought scenarios, animations, video, and simulations, participants progressively distinguished mass from weight; recognised gravity as attractive and distance-dependent; and reconsidered the assumption that gravity vanishes in the region between the Earth and the Moon. They also developed a view of the Earth and Moon as a dynamical two-body system rotating about a common centre of mass. Refining an existing Static Tide Model by incorporating the Moon's dynamical motion supported a more coherent account of the simultaneous formation of two tidal bulges and functioned as a bridge

towards scientifically compatible conceptual understanding. Overall, the results position tides as a productive phenomenon for linking concepts often taught separately (gravity, reciprocity of forces, inertia, two-body systems, barycentre) and for engaging learners with modelling as a means of explanation.

Methodologically, the study is limited by a small, focused sample (N=16) and by data generated within a specific instructional sequence; generalisation should therefore be cautious. Future work should examine the durability of conceptual change over time and across contexts (e.g., other departments, in-service teachers, upper secondary students), as well as transfer into authentic classroom practice. Interdisciplinary connections with Geography or Earth Sciences may further enhance relevance by foregrounding tidal effects in coastal regions. Finally, cross-cultural studies could explore how interpretive resources shape understandings of tides and the outcomes of comparable interventions.

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Learning Chemistry Through A Concept Map With Clickable Digital Resources (Hypermedia Map)

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Although concept mapping is not new in science education, a few studies systematically evaluate it as a multimedia and hypermedia study material. Seemingly, several factors may influence the effectiveness of meaningful learning. This study investigated the effects of students' prior knowledge and the use of digital resources (i.e., clickable concepts on the map) on learning outcomes and cognitive load. A chemical macroscopic event – electrical conductivity in metals – was chosen to be represented in a teacher-prepared map used as study material. According to Mayer's Cognitive Theory of Multimedia Learning, hypermedia materials may foster schema construction; however, for lower prior knowledge learners, it could lead to a cognitive overload due to a high demand of essential processing on the verbal channel. A 2 x 2 pre-test-to-post-test design was adopted to investigate the effect of map type (Plain map vs. Hypertext map) and learners' prior knowledge (Low vs. High) on test performance and mental effort ratings for understanding the topic. The participants were 77 undergraduate students treated following APA ethical guidelines for human research. The results showed that the Hypertext map-type group had a higher performance with a lower mental effort than the Plain map group. Surprisingly, no prior knowledge effect was found. Adding clickable digital resources on the map enhanced factual and conceptual scientific knowledge for both groups of learners (low and high prior knowledge), indicating a no-overload situation.

Keywords: Digital Resources. Higher Education. Multimodal Learning.

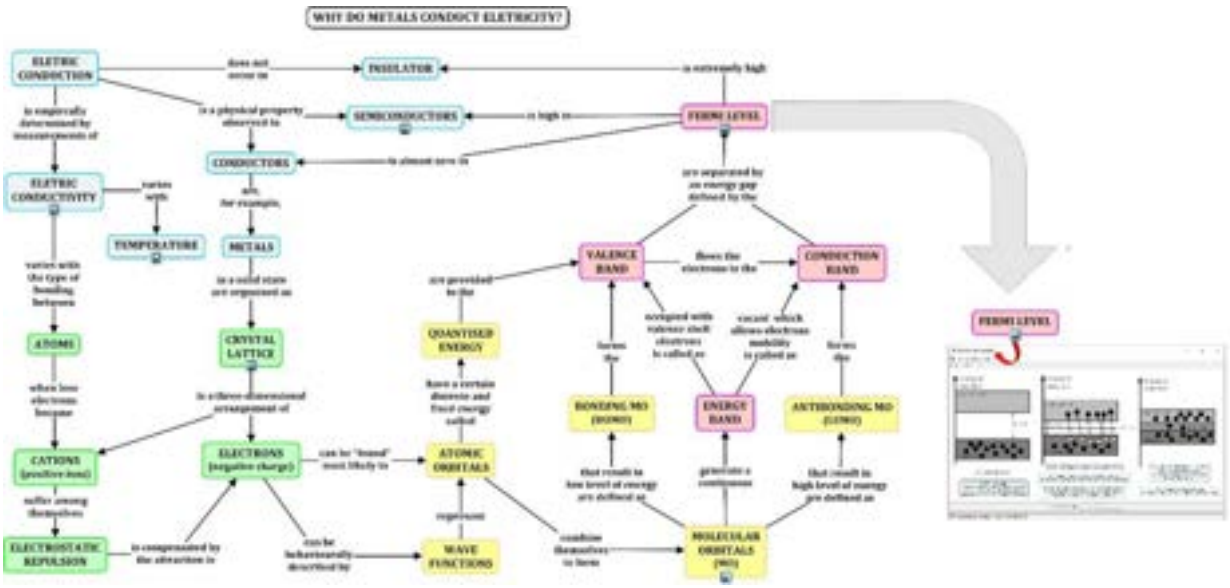
Theoretical Framework And Purpose

Concept maps or Cmaps (Figure 1) have been described in the literature as a pedagogic tool that supports meaningful learning (Novak, 2010) because they are organised similarly to the knowledge structure in memory (Ausubel, 2000). They can also incorporate multiple sources of information, including verbal/textual and visual/pictorial. Both features facilitate accessing and integrating information processes, which scaffold meaningful learning (Paivio, 1990).

Although using Cmaps is not new in education, a few studies systematically evaluate them as media and hypermedia study material (Chang, Hwang, & Tu, 2022). Moreover, several factors seemingly influence the effectiveness of learning through Cmaps, such as the learners' Prior Knowledge (PK) (e.g., Amadieu et al., 2009; Simonsmeier et al., 2021) and the use of Digital Resources (DR) resulting in a hypermedia map (e.g., Chiou, Tien, & Lee, 2015; Fatawi et al., 2020).

According to the Cognitive Theory of Multimedia Learning (Mayer, 2009), hypermedia materials, such as concept maps with clickable concepts (Figure 1), may foster schema construction. However, for lower PK learners, this could lead to cognitive overload due to a high demand of essential processing on the verbal channel, which means selecting and organising relevant information in the limited working memory.

Figure 1: Teacher-prepared concept map used as study material (on the left-hand). The hypermedia map was prepared by adding six clickable digital resources on the concepts (see an example on the right-hand).



The present study investigated the effect of learners' PK and the use of DR on learning outcomes and mental effort through concept mapping instruction. If adding DR is responsible for fostering learning, participants in the hypermedia map group are expected to have higher performance (Hypothesis 1a) and lower mental effort (Hypothesis 1b) than the plain map group. On the other hand, if adding extra information on the map would lead to an overload situation, the low PK group is expected to have lower performance (Hypothesis 2a) and higher mental effort (Hypothesis 2b) than the high PK group.

Methods

A 2 (Prior Knowledge: Low, LK *vs.* High, HK) x 2 (Map type: Plain Map, PM *vs.* Hypertext Map, HM) factorial design was adopted, resulting in four conditions: LKPM group (n = 16), LKHM group (n = 24); HKPM group (n = 18) and HKHM group (n = 19). The participants were 77 undergraduate Chemistry students (51% female, M_{age}: 22.1) treated following APA ethical guidelines for human research. The data collection procedure occurred during a university-level class (approximately 60 minutes) of a natural science course as follows.

- *Step 1 - PK test (5 min)*: students were asked to judge a 25-statement questionnaire about the chemical content as correct/incorrect, considering +1 for correct judgments and -1 for misjudgments (-10 to +10 scale). Example of statements: In metals, there is not actually a bond, only a weak interaction (false); metals have atoms spatially organised in the form of a crystalline lattice (true). The questionnaire was peer reviewed to eliminate dubious information. The internal consistency analysis of the items revealed satisfactory results for Cronbach's alpha, with a value of 0.762.
- *Step 2 - Pre-test (10 min)*: six multiple-choice questions assessed factual knowledge, and four written questions assessed conceptual knowledge. Overall performance was given by the sum of both tests (0-10 scale). Example of multiple-choice question: "In a metal, electrostatic interaction occurs between: (A) Cations and anions; (B) Protons and electrons; (C) Cations and electrons (CORRECT); (D) Protons and anions; (E) Neutral atoms". Example of a written question: "Why are metals good conductors of electricity?"

- *Step 3 - Navigating on the Cmap (20-30 min)*: the digital plain Cmap was prepared by the teacher to explain conductivity in metals (Figure 1). To understand this phenomenon, the learners must grasp chemical concepts regarding the types of materials (insulators, semiconductors and conductors) and macroscopic aspects of electrical conduction (blue concepts in Figure 1); the reticular model for crystalline structure of metals (concepts in green); the Theory of Molecular Orbitals, HOMO and LUMO formation (concepts in yellow) and the Band Theory of Solids and Fermi level (concepts in pink). The hypermedia map was prepared by adding six DR on the map, which means six clickable concepts that pop up images and further explanation about the topic (see Figure 1). The DR was: images, tables, audio explanation, videos, simulation and animation. The concepts that received the DR were: electric conduction, temperature, semiconductors, crystal lattice, molecular orbitals and Fermi level (Figure 1).
- *Step 4 - Mental effort rating (5 min)*: students were asked to rate their mental effort (Paas et al., 2003) to navigate and understand chemical content on the Cmap by using a 9-point Likert scale (from 1 = very, very low to 9 = very, very high).
- *Step 5 - Post-test (10 min)*: the students were asked to answer six multiple-choice questions (retention test) and four written questions (transfer test). Overall performance was given by the sum of both tests (0-10 scale). The post-test was different and more difficult than the pre-test.

Results And Discussion

A 2 (Prior Knowledge: LK vs. HK) x 2 (Map Type: PM vs. HM) ANOVA and independent t-tests were conducted using SPSS 24.0 (IBM, USA) on pre-test and post-test overall performance and their difference (i.e., gain of knowledge) and mental effort ratings (Table 1).

One-way ANOVA confirmed that PK test scores were higher for HK participants (M = 4.97, SD = 2.13) than for LK ones (M =- .60, SD = 2.29), $F(1,75) = 122.01$, $p < .001$. As expected, HK participants outperformed LK on pre-test, $F(1,75) = 9.24$, $p < .005$. Concerning post-test performance, the ANOVA confirmed that neither PK nor map type affected the post-test scores, $F(1,75) = .02$ and .03 (both ps > .05), respectively. On the other hand, it was a main effect of adding DR on the map, considering the gain of knowledge. The HM group gained more factual and conceptual knowledge than the PM group, $F(1,75) = 3.82$, $p < .05$, $\eta^2 = .15$ (medium effect size). Yet no significant difference emerged between the groups considering their level of PK, $F(1,75) = 1.70$, *n.s*.

There is some evidence that offering a Cmap as hypermedia study material fostered learning, confirming Hypothesis 1a. As the level of PK did not affect students' performance, it was inferred that adding DR on the map did not lead to an overload situation, refuting Hypothesis 2a.

The ANOVA showed a main effect of students' PK on mental effort. LK students reported higher mental effort (M = 7.24, SD = 1.00) to navigate the map and understand the topic than HK students (M = 4 .93, SD = 1.40), $F(1, 75) = 6.05$, $p < .05$, $\eta^2 = .08$ (medium effect size). This confirms our Hypothesis 2b. Yet no significant difference emerged between the groups considering the use of DR, $F(1,75) = .02$, *n.s*.

Table 1: High and low PK participants' means (SD) of pre-test, post-test, knowledge gain and mental effort for each Cmap type.

	Low Prior Knowledge (LK)		High Prior Knowledge (HK)	
	Plain Map (PM)	*Hypermedia Map (HM)*	*Plain Map (PM)*	*Hypermedia Map (HM)*
PK test scores	-.12 (2.12)	-.92 (2.38)	5.00 (2.37)	4.95 (1.93)
Pre-test	2.44 (1.54)	1.96 (1.22)	3.61 (1.94)	2.82 (1.33)
Post-test	4.13 (1.94)	4.29 (1.70)	5.06 (1.64)	5.00 (1.97)
Gain of knowledge	1.69 (1.65)	2.33 (1.90)	1.44 (1.76)	2.18 (1.78)
Mental effort	8.04 (.48)	6.43 (1.38)	4.04 (1.38)	5.81 (1.42)

Interestingly, a marginal PK x map-type interaction was found considering mental effort, $F(1,75) = 3.81$, $p = .05$, $\eta^2 = .05$ (small effect size). Whilst for LK learners, adding DR to the map has decreased mental effort, $t(38) = 4.47$, $p < .05$, for HK learners, adding DR increased it, $t(35) = -3.13$, $p < .05$. Moreover, a high PK on the topic was critical to decrease the mental effort required to understand the content on the plain map (LKPM *vs* HKPM, $t(32) = 11.00$, $p < .001$). However, no difference was found for those who studied the hypermedia map (LKHM *vs* HKHM, $t(41) = 2.21$, *n.s.*). These results are partially in line with our Hypothesis 1b.

These results suggest that for LK students, the Cmap used as hypermedia study material leads to higher performance with lower mental effort. Considering a no-overload situation, they were able to select relevant information and organise it as presented without imposing a high cognitive demand on their limited working memory. Consequently, they can use some free cognitive resources for schema construction (i.e., learning).

For HK learners, the increase in mental effort can be explained by generative processing, which means actively engaged in the learning process. This is only possible due to the automated schemas in long-term memory, which can be retrieved and integrated with new knowledge presented in the material. These results showed no evidence of an overload situation nor the expertise reversal effect (Kalyuga et al., 2003), which means, "instructional techniques that are highly effective with inexperienced learners can lose their effectiveness and even have negative consequences when used with more experienced learners" (p. 23).

Final Remarks

Although Cmaps have been used for the last five decades in Science Education, a few studies systematically evaluate them as a teacher-prepared media and hypermedia instructional material. Firstly, ensuring a well-designed digital Cmap (readability, layout and content accuracy) is critical for learning with a hypermedia map. In this study, using the Cmap with clickable DR fostered learning regardless of the level of learners' PK. However, for a higher learning outcome,

we need to be aware of its impact on knowledge acquisition, avoiding cognitive overload and the expertise reversal effect.

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Learning A Respiratory Model – Undergraduate Understanding Of And Attitudes Toward The Fick Equation

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This study examines how second-year biology students in an animal physiology course understand and apply the Fick equation, a fundamental mathematical model in respiratory physiology, and their attitudes toward the use of mathematical expressions in the discipline. Seventy-one students completed a written assignment designed to assess their understanding of the Fick principle, followed by a questionnaire exploring their attitudes toward mathematical models in physiology. Results indicate that many students struggled to articulate their understanding of the Fick principle in precise scientific language, with many answers being vague or colloquial. While some students referenced the Fick equation, only a few correctly applied its elements in their explanations. Additionally, misconceptions about alternative oxygen-binding pigments, such as myoglobin or hemocyanin, were prevalent. The questionnaire revealed two distinct student profiles: one with a positive attitude toward models, finding equations helpful for understanding and remembering concepts, and another with a negative attitude, viewing models mainly as tools for numerical calculation in exam preparation. The findings suggest that while students recognize the importance of models in physiology, they struggle to translate mathematical representations into scientifically accurate conceptual knowledge. This supports previous research on the fragmentation of mathematical and disciplinary knowledge. This study highlights the need for improved instructional strategies to help students translate mathematical models into scientifically accurate conceptual knowledge.

Keywords: Attitudes, conceptual understanding, undergraduate learning

Introduction

Representational models are central to science education, where they are used to abstract and simplify complex real-world phenomena, rendering them more amenable to analysis. Such models frequently include mathematical representations, which play a crucial role in scientific reasoning and problem-solving. Despite their importance, research has consistently documented substantial challenges for students in applying mathematics meaningfully within scientific contexts A recurrent issue is the fragmentation of mathematical and disciplinary knowledge, which impedes students' ability to integrate concepts and develop coherent understandings (Towns et al., 2019). As a result, mathematical representations are often perceived as purely algebraic or symbolic tools, encouraging procedural manipulation of variables rather than conceptual interpretation (Taber, 2009; Tsui & Treagust, 2013).

These difficulties are also evident in physiology. Prior studies have reported persistent student misunderstandings of physiological and respiratory models (Michael et al., 1999; Modell, 1997). In line with these findings, our observations suggest that students frequently struggle to conceptualize the Fick equation, a foundational mathematical model in respiratory physiology.

Against this backdrop, the present study focuses on students' attitudes toward the Fick equation as a mathematical model, with particular attention to how the model is used in practice. Attitudes are commonly understood as the feelings, beliefs, and values individuals hold about science as an object and are typically conceptualized as a multifaceted construct comprising affective,

cognitive, and behavioural components. This includes enthusiasm for and enjoyment of science, perceptions of science, views on the societal contributions of science and scientists, and orientations toward engagement with science, such as interest in science-related careers (Osborne et al., 2003). However, attitudes are rarely examined in relation to epistemic dimensions of the discipline, such as the nature of biological knowledge or the epistemic status of models (e.g., whether they are explanatory, predictive, or heuristic). Consequently, students' resistance to mathematical models may be misinterpreted as affective in origin, when it is instead epistemically grounded (Aikens et al., 2021).

This study therefore examines how biology students interpret and apply the Fick equation as a mathematical model in physiology and explores their attitudes toward the use of mathematical expressions within the discipline. The study is guided by the following research questions:

1) How do biology students apply Fick's principle to solve a given assignment?

2) What attitudes do students express toward the use of mathematical expressions in physiology?

Method

Our target group consisted of second-year undergraduate biology students enrolled in an animal physiology course. The course included lectures, theoretical exercises, and laboratory sessions. The Fick principle had been covered in the previous lecture and was revisited during the lecture in which the study took place.

For the study, we developed a pen-and-paper format comprising a written assignment and a brief questionnaire. The written assignment was designed to assess students' understanding of the Fick principle and the extent to which they utilized the Fick equation. The assignment posed the following question:

"Some Antarctic fish lack haemoglobin in their blood entirely. It has been observed that these fish have larger hearts compared to closely related species with haemoglobin. Provide a brief explanation for this."

The Fick equation was provided at the top of the assignment, but its use was not explicitly required. Students were instructed to keep their textbooks closed while answering.

To explore students' attitudes toward mathematical models in physiology, we designed a questionnaire consisting of nine items, which students completed immediately after the written assignment.

A critical analysis of these items indicated that they capture multiple constructs beyond affective attitude. Specifically, some items reflect epistemic engagement and perceived utility (e.g., "The Fick principle is easier to understand when expressed as an equation than when described in words"), others measure self-efficacy (e.g., "I understand the Fick principle well enough to explain it to other students"), while several items capture instrumental motivation or behavioral intention (e.g., "I focus on the text and usually skip the equations") or disciplinary identity (e.g., "Equations do not belong in a physiology textbook"). Recognizing these distinctions is important for interpreting survey responses, as apparent "attitudes" may in fact reflect epistemic beliefs, confidence, or task-specific engagement rather than stable affective dispositions.

Analysis

Fifty-two students (73%) completed the assignment, while 19 students (27%) did not participate. The responses were reviewed by two researchers and analysed to address the first research question. The answers were categorized and quantified for further analysis.

The unit of analysis comprised individual student responses to the assignment, based on their handwritten answers. A structured qualitative content analysis was conducted following Mayring's (2015) procedure. First, categories were defined to capture analytically relevant features of the responses, specifically the degree of conceptual correctness and the presence of identifiable misconceptions. Second, explicit coding rules were established to ensure consistent delineation between categories and unambiguous assignment of each response segment to a single category. Third, anchor examples were selected to exemplify typical manifestations of each category, illustrating both accurate reasoning and recurring patterns of misconception.

Of the 71 questionnaire responses, all were deemed valid for statistical analysis. Reliability, measured as internal consistency, was calculated using Cronbach's alpha, yielding a value of 0.71. To ensure consistency in the analysis, negatively worded statements about models (items 2, 5, 7, and 8) were recoded.

Due to the relatively small sample size, advanced statistical analyses were not meaningful. Our primary aim was to examine how responses were distributed across the individual items and to identify the overarching conclusions that could be drawn from these patterns. The results are therefore presented as response distributions to facilitate straightforward interpretation.

Results

The results revealed that many students struggled to articulate their answers in clear and concise scientific language. A correct answer would include the following reasoning:

The arterial oxygen concentration (CaO2) is low in fish lacking haemoglobin, leading to a reduced arteriovenous oxygen difference. To ensure sufficient oxygen transport, the cardiac output (Q) must be increased. This can be achieved by a higher heart rate (fH) and/or a larger stroke volume (Vs). The most critical factor is the larger stroke volume, which is facilitated by a larger heart.

However, many student responses were vague and imprecise. Thirty-nine students (54%) provided answers referencing the need to "pump a greater blood volume," but these were often formulated using colloquial rather than scientific language. Representative examples include:

"Could be because more 'liquid' must be pumped around than if it had been blood, because the 'liquid' does not contain so much oxygen".

"Haemoglobin binds oxygen very efficiently. Without haemoglobin, a greater heart is required to get the same amount as with haemoglobin".

"With a great heart blood is pumped around faster. And therefore, more oxygen is also pumped around in the body of the fish".

While these answers are not entirely incorrect, they lack scientific precision. The students seem to exhibit an intuitive grasp of the concepts but face challenges in translating their understanding into scientifically accurate language. This imprecision does not necessarily indicate a

misunderstanding of the Fick principle but rather highlights difficulties in expressing conceptual knowledge in a formal scientific context.

Only 4 responses (6%) explicitly incorporated elements from the Fick equation. For instance:

"A larger heart enables better circulation of body liquid (blood), which is necessary when the fish lacks haemoglobin which binds oxygen. Stroke volume, Vs, enters the Fick principle. The greater Vs → the greater VO_2".

Table 1. The results are expressed as a percentage of the total number of students who replied to the questionnaire (n = 71)

	Item	Strongly agree	Agree	Disagree	Strongly disagree
1	When I prepare for lectures in physiology, I spend a considerable amount of time trying to understand equations	8	42	39	11
2	When I prepare, I focus on the text and usually skip the equations	21	36	31	12
3	The Fick principle is easier to understand when expressed as an equation than when described in words	3	40	50	7
4	It is easier to remember the Fick principle when it is presented as an equation	23	58	17	2
5	I can only use the Fick equation when I can insert values	9	44	29	18
6	I understand Fick principle well enough to explain it to other students		18	46	36
7	I am only trying to understand the equation because it is curriculum	12	30	38	20
8	In my opinion, equations do not belong in a physiology textbook		6	25	69
9	Understanding and using equations in physiology is part of scientific literacy	69	29	2	

Additionally, 11 students (16%) suggested that the fish might use alternative oxygen-binding pigments, such as myoglobin or hemocyanin, instead of haemoglobin. These responses reflect misconceptions. For example:

"They have myoglobin or something like that, which can only bind 1 oxygen, and more blood therefore has to be pumped to give the same amount of oxygen to the body".

"The Fish have hemocyanin(?) in their blood. This transports oxygen and also has to be pumped around the body to the tissue; perhaps hemocyanin cannot carry as much oxygen as haemoglobin?

(The haemoglobin molecule binds 4 oxygen atoms, but I don´t know how much hemocyanin binds!)".

These examples show that students are reasoning sensibly and attempting to integrate prior knowledge with the question. For instance, they understand that myoglobin has fewer oxygen-binding sites than haemoglobin and hypothesize that this could necessitate increased blood flow. However, their factual knowledge is incorrect, as fish blood does not contain myoglobin or hemocyanin. This misunderstanding leads to flawed conclusions.

Overall, these findings suggest that while students' conceptual models align with those presented in lectures, exercises, and textbooks, errors in factual recall and imprecise language hinder their ability to provide scientifically accurate explanations.

The analysis of the questionnaire revealed that the students could be divided into two nearly equal groups, each characterized by a distinct profile.

The first profile represents students with a positive attitude toward models. These students view themselves as actively engaging with models, finding them helpful for understanding and remembering concepts. Specifically, they report that the Fick principle is easier to comprehend and recall when expressed as an equation rather than in words.

The second profile represents students with a negative attitude toward models. These students tend to skip equations in their textbooks, viewing the Fick equation as merely a tool for numerical calculations. Their primary motivation for understanding the Fick principle is limited to exam preparation.

Interestingly, this negative attitude is inconsistent with responses to items 8 and 9 on the questionnaire. In item 8, nearly all students disagreed with the statement that models do not belong in a physiology textbook, and in item 9, most agreed that understanding and using equations in physiology is integral to scientific literacy. This apparent contradiction suggests that while students acknowledge the importance of models as an ideal aspect of physiology and scientific literacy, their everyday experiences with models in lectures and exercises may not align with this ideal.

Discussion

This study examines how undergraduate biology students interpret and apply the Fick equation as a mathematical model in respiratory physiology, and how they articulate their epistemic stance toward mathematical formalisms within the discipline. Consistent with prior research documenting the fragmentation between mathematical and disciplinary knowledge (Towns et al., 2019) and students' tendency to operationalize equations as procedural algorithms rather than conceptual representations (Taber, 2009; Tsui & Treagust, 2013), our findings demonstrate that the majority of students failed to mobilize the Fick equation as an explanatory framework – even in contexts where its application was explicitly warranted.

RQ1: How Do Biology Students Apply Fick's Principle To Solve A Given Assignment?

Although most students produced responses that were compatible with the intended explanation (e.g., "a greater volume must be pumped"), only a small minority explicitly grounded their reasoning in the structure of the Fick equation. This pattern indicates that many students relied on informal physiological intuition rather than using the equation as a representational model

linking oxygen uptake (VO_2), cardiac output (Q), and the arteriovenous oxygen difference (CaO_2–CvO_2). The equation thus failed to function as an epistemic tool for explanation, remaining largely implicit or entirely absent from students' reasoning processes.

Importantly, the widespread vagueness and colloquial phrasing should not be interpreted as conceptual failure. Instead, it may reflect a recurring educational bottleneck: students may recognize the causal logic of oxygen transport but struggle to articulate it in concise scientific language and to map that logic onto formal representations. This aligns with the idea that representational competence involves not only "knowing the content" but being able to translate between verbal, conceptual, and mathematical forms (Kozma & Russell, 1997). Thus, the main barrier appears to be representational integration rather than a complete lack of physiological understanding.

At the same time, responses containing alternative oxygen-binding pigments (e.g., myoglobin, hemocyanin) reveal that misconceptions do play a substantive role for a notable subset of students. These answers were often framed through seemingly coherent reasoning ("fewer binding sites → lower oxygen transport → increased pumping"), suggesting that misconceptions were not random errors, but plausible reconstructions based on fragmented prior knowledge. This supports earlier work showing that students may hold internally sensible but scientifically inaccurate models of physiological mechanisms (Michael et al., 1999; Modell, 1997). Here, factual inaccuracies about oxygen carriers led students to build explanations that were structurally reasonable yet physiologically invalid – illustrating how misconceptions can be reinforced by otherwise productive mechanistic thinking.

Taken together, these findings suggest a heterogeneous landscape: while students' explanations often reflect partial conceptual alignment with teaching materials, their performance is constrained by (1) limited use of the equation as a conceptual scaffold, (2) imprecision in disciplinary discourse, and (3) discrete yet consequential misconceptions that derail otherwise plausible reasoning.

RQ2: What Attitudes Do Students Express Toward The Use Of Mathematical Expressions In Physiology?

The questionnaire data reveals two nearly equal attitudinal profiles: one group positioned equations and models as cognitively supportive (supporting comprehension and retention), whereas the other positioned them as obstacles or as purely instrumental for calculation and exam performance. This division resonates with the literature on students' procedural orientation toward mathematics in science: for a substantial cohort, equations remain symbolic artefacts to be manipulated or avoided, rather than representations of relationships in biological systems (Redish & Kuo, 2015).

However, a key finding is that the "negative" profile did not reflect wholesale rejection of models. Students who reported skipping equations nevertheless tended to endorse the normative legitimacy of models in physiology textbooks and acknowledged that using equations is part of scientific literacy. This discrepancy suggests that resistance may not be rooted in anti-scientific affect or motivational deficits but rather in epistemic and experiential factors: students may accept the principle that models should function as explanatory resources while simultaneously experiencing them as disconnected from understanding in pedagogical practice. This interpretation aligns with Aikens et al.'s (2021) argument that what appears to be negative attitude

may instead reflect students' perceptions of the epistemic role that models are afforded in teaching – whether models are treated as explanatory resources or merely as formalities attached to numerical exercises.

Consequently, students' attitudes appear to be shaped by how mathematical representations are positioned within the instructional context. If the Fick equation is primarily encountered as something to "plug numbers into," students may reasonably conclude that it is not a tool for thinking, but as an assessment hurdle. Conversely, students who experienced the equation as a compact summary of causal structure were more likely to report it as meaningful and memorable. Attitude, then, is not simply an individual trait but plausibly an outcome of students' repeated encounters with what counts as "doing physiology" across lectures, exercises, and examinations.

Implications: The Fick Equation As A Model Rather Than A Formula

Across the dataset, the central pattern indicates that students often possess fragments of correct reasoning but fail to integrate these consistently with the formal mathematical model. This finding directly instantiates the problem articulated in existing literature: the fragmentation of mathematical and disciplinary knowledge (Towns et al., 2019) and the reduction of equations to procedural tools (Taber, 2009; Tsui & Treagust, 2013). The Fick equation appears to function as a boundary object (Star & Griesemer, 1989) that some students successfully employ to coordinate conceptual domains, while others perceive it as an external mathematical demand imposed upon physiological reasoning.

A plausible educational implication is therefore that instruction should make the epistemic status of the equation explicit: not only what it is, but what it is for. If the Fick equation is framed as a representational model that explains why changes in CaO_2, Q, fH, and Vs matter, students may be better positioned to move from intuitive statements ("pump more") to mechanistically grounded explanations ("reduced CaO_2–CvO_2 requires increased Q, primarily via increased Vs enabled by a larger heart"). At the same time, the misconceptions observed indicate the need for targeted conceptual clarification of oxygen carriers and their distribution across taxa, because incorrect recall can produce coherent but incorrect explanatory pathways.

Conclusion

In response to the research questions posed, we find that undergraduate biology students predominantly approach the assignment through intuitive physiological reasoning but rarely deploy the Fick equation explicitly as an explanatory model; furthermore, a subset of students' reasoning is undermined by misconceptions concerning oxygen-binding pigments. Attitudinally, students divide into two approximately equal cohorts – those who experience equations as conceptually generative scaffolds and those who perceive them as calculational or examination-driven obstacles – yet even students in the latter category largely acknowledge the disciplinary legitimacy of mathematical modelling. This constellation of findings suggests that students' difficulties and resistance may stem less from mathematics aversion per se than from how mathematical representations are positioned and operationalized within physiology pedagogy: as epistemic tools for mechanistic reasoning, or as symbolic formalism for algorithmic manipulation.

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Models As Artefacts From The Perspective Of Instrumental Genesis

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In science and science education, models play an essential role. Scientific models have a representational aspect, but they also serve other epistemic practices for the agents that are manipulating and using them, such that models can be seen as human-made epistemic artefacts. We see a parallel between an agent's use of models and of technologies. The instrumental approach focusses on the relation between cognition and the use of technology considered as a materialized artefact through instrumental genesis. Instrumental genesis is the complex process of an artefact becoming an instrument with a certain purpose for the user through the user's cognitive and practical interactions with the artefact. This paper explores the possibilities of applying the notion of instrumental genesis to students' interactions with models as artefacts. We present an empirical example of Danish upper secondary school biology students conducting an experiment on diffusion. Using agar blocks as a model for cells, the purpose of the exercise was for the students to learn about diffusion in cells. The analysis of the empirical example indicates that the perspective of instrumental genesis can provide a valuable terminology for understanding students' use of models as epistemic artefact. Furthermore, knowledge of instrumental genesis may help structuring learning activities to support students' development with models, considered as a form of modelling genesis.

Keywords: Science models, epistemic artefacts, instrumental genesis

Introduction

In a first approximation, models can be seen as the appropriation of materiality to serve epistemic purposes. Similarly, technology is an appropriation of materiality to serve pragmatic purposes. This paper addresses the interplay between these two perspectives on interactions with materiality. In philosophy of science, the so-called artefactual view on the nature of models (e.g., Knuuttila, 2011) considers models as epistemic artefacts, which involves a triadic relation between the agent, the model, and the represented part of the world. In this sense, the representative aspect of a model occurs when the model is used by an agent (Giere, 2010). From the artefactual view, models are human made artefacts materialized serving many epistemic functions other than representing the world. It is in the interaction with models, such as producing, manipulating and using models that scientists can generate knowledge (Knuuttila, 2011). For the teaching and learning of science, epistemic functions of models are essential (Taber, 2017), as models in education have a didactical purpose based on an intension for the learning. This means that in learning situations, we can also consider models as epistemic artefacts that the students are to learn with. We find it interesting to study students' cognitive processes when interacting with models as epistemic artefact. To do this, we analyse an empirical example of a biology experiment on diffusion in cells, where students are studying the relation between cell size and diffusion rate.

Considering models as artefacts may create a parallel between the use of technology and models for epistemic purposes. One theoretical perspective on the relation between technology and cognition from educational research is the instrumental approach (Verillon & Rabardel, 1995). In mathematics education research, the notion of instrumental genesis (Guin & Trouche, 1998) builds on the instrumental approach and provides a framework for studying students' interaction with artefacts in learning situations. Instrumental genesis is the lengthy process of interacting with and learning from an unknown artefact such that it becomes an instrument with a specific purpose for the student (Guin & Trouche, 1998). Therefore, we find it relevant to study students' work and interactions with scientific models as artefacts by addressing the following question: *What possibilities to study students' interactions with scientific models as epistemic artefacts may the perspective of instrumental genesis offer?*

We address this question by applying the theoretical notion of instrumental genesis on the empirical example from a Danish upper secondary school biology class.

Empirical Example: Diffusion In Cells In Upper Secondary Biology

The chosen empirical example stems from a project on models and modelling in STEM education, where we have observed upper secondary teaching in biology, physics and chemistry for the past year. In a 1st year biology class of Danish upper secondary school (corresponding to grade 10 or 11), the students were learning about diffusion in cells. We observed one of the activities, which revolved around an experiment designed to explain the relation between the size of a cell and the degree of diffusion across the cell membrane. This experiment was well-known to the biology teacher who previously had run the experiment with other 1st year biology classes. The students followed written instructions for executing the experiment and did a written report on the experiment afterwards.

The students worked in small groups, immersing three different sized cubes of blue-coloured alkaline agar into vinegar (see Figures 1a and 1b), and leaving them for exactly five minutes. Subsequently, the cubes were cut in halves (see Figure 1c), making it possible to measure how far into the cube the vinegar had diffused, and thus calculate the ratio between the surface area and volume of the cube, and the volume of the diffused area. The students were then asked to write a report on the experiment and their findings, including their reflections on the use of models in the experiment as well as in the theory connected to the topic.

Figure 1a. The three alkaline agar blocks before they are put into vinegar.



Figure 1b. The three agar blocks in vinegar.

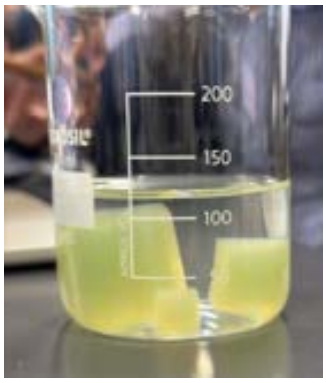


Figure 1c. The three agar blocks cut into halves after the diffusion of vinegar.



Models As Epistemic Artefacts

Viewing models as human-made epistemic artefacts makes it possible to nuance the complexity of the links between models and reality. One of the links is that models are simplified representations of reality based on some selected criteria (Gilbert, 2004). In addition to representing, models may be used to perform other epistemic practices such as "making simplifications and idealization; conceptualizing imagined (or non-observable) objects or processes; supporting arguments, explanations, and predictions" (Gilbert & Justi, 2016, p. 23). Therefore, models may be seen as external artefacts, which play an important role in thinking and learning, when using and producing them. Thereby, models are seen independently from the real-world target systems (Knuuttila, 2011), and the relation between the model and the subject using the model becomes essential. This view on models is highly relevant in an educational context, as models, such as 2-D illustrations, 3-D figures, symbolic formulas, animations, and laboratory exercises, all play a central part for learning science. Students' access to study, conceptualize, explain and investigate scientific phenomena often is through educational science models.

Instrumental Genesis

In the notion of instrumental genesis, an artefact is an either physical or symbolic materialized object that a student or user encounters for the purpose of handling a given task or situation. Instrumental genesis is the cognitive process of interacting with the artefact to become familiar with it and with ways of using it such that it becomes an instrument for the specific task or situation. Through this interaction students learn from the artefact and develop knowledge about the given situation and its objects and phenomena (Guin & Trouche, 1998). The interaction is two-way directional in the sense that the student is influenced by the artefact and its configuration and limitations, named instrumentation. On the other hand, the student reads their own anticipations and intentions into the artefact and makes use of the artefact in an individual way, named instrumentalization. To interact with an artefact, students make use of *techniques*. A technique is a way of solving a task or handling a situation, based on reasoning and previous experiences and routines (Artigue, 2002). These techniques can either be of pragmatic or epistemic value. The pragmatic value is related to the technique's productive potential such as providing answers and facts. The epistemic value concerns the technique's contribution and support to the learner's cognition such as understanding the scientific object and processes involved (Artigue, 2002). A pragmatic technique when using a computer algebra system in mathematics could be to solve an equation efficiently without the technique supporting an understanding of why the result is correct or how to solve that type of equation in general. An epistemic technique could be to use the computer algebra system to do multiple calculations or manipulate a variable to look for patterns of why a certain relation is valid, where it is rather the process behind the result than the result itself that is of interest. The value of the applied technique is often related to the given instructions and the types of tasks, and sometimes pragmatic techniques may be used as part of or as precursor to epistemic techniques.

We suggest that a similar distinction between techniques can be applied to students' work with scientific models. Pragmatic techniques involve using models to obtain specific results, such as perform measurements, read off values or predictions. In contrast, epistemic techniques involve using models to explore relationships, mechanisms, assumptions, and limitations in order to develop understanding of underlying processes and systems of the phenomena represented. By identifying students' techniques for using models, we can gain insight into how students engage

with models as epistemic artefacts. Focusing on students' techniques for applying models in science education provides a lens to study their interactions with models, as it is the students' cognitive processes and their interactions with the models that ultimately determine what students take from the models.

Method

The presented empirical example was selected because the students work with concrete artefacts in the form of agar blocks, which function as models of cells or, more precisely, of cell sizes. In this way, the experiment itself constitutes a model of the relationship between cell size and diffusion. The example provides an empirically rich setting for analysing students' interactions with models, as the agar blocks are initially unfamiliar and require the students to develop techniques for using them efficiently for the experiment. This makes it possible to examine how students' pragmatic and epistemic techniques emerge and develop over the course of the activity, and to explore whether the notion of instrumental genesis can serve as an analytical lens for studying how models function as epistemic artefacts, namely, tracing how an artefact becomes a meaningful model for understanding the underlying relationship.

The observation of the example was carried out by the first and the second author. All observations were video recorded with two classroom cameras. The data collected from the observations are field notes, video and audio recordings of classroom teaching and of group work and student products.

As part of the analysis of the empirical example, we identified the main activities of carrying out the experiment, such as cutting and treating the agar blocks of the three sizes, doing measurements and calculations after the experiment, and discussing their results in relation to the given question of cell size and diffusion rate. These activities include the students' techniques for treating the agar blocks and the experiment as models for cells and diffusion. Thus, analysing what the students do with the materials and for what purposes indicate whether a technique is pragmatic in the sense of solving a specific task of the experiment, or epistemic in the sense of supporting knowledge about the size of a cell. This means that also the students' way of talking about the materials and the activities are part of their techniques.

Furthermore, the students were asked to discuss their results and to explain how the experiment can account for the relationship between cell size and diffusion in their written reports. Analysing the written discussions provides access to the students' reflections on the experiment as an artefact and makes it possible to examine how the experiment comes to function as an instrument for understanding the relationship between cell size and diffusion through the students' engagement with it. The reflections make visible how students interpret the model, how they attribute meaning to it, and how they derive information that is relevant for the phenomenon under study. In this way, the written reports provide insight into the ongoing process of instrumental genesis.

In analysing the written reports, the distinction between pragmatic and epistemic techniques is not used as a categorical coding of students' responses, but as an analytical guideline for relating the written work to the students' activities during the experiment. When students' written responses are primarily oriented towards reporting results obtained in the experiment, this points to the role of pragmatic techniques, insofar as the focus is on accomplishing the experimental task and presenting outcomes. When, on the other hand, students discuss their results in relation

to the experimental materials and the underlying process of diffusion, this points to the role of epistemic techniques, as the model is used to reason about and make sense of the relationship between cell size and diffusion. Importantly, both orientations may be present within the same written response, and it is precisely the interplay between pragmatic and epistemic techniques across activities and reflections that is of interest in analysing the process of instrumental genesis.

Instrumental Genesis In A Biological Experiment

When the students began the experiment, they had been introduced to its purpose and to the material of alkaline agar blocks and the chemical reaction happening between the agar and the vinegar. Yet the students were still rather unfamiliar with the material they were to work with, in particular the alkaline agar. At first, the students studied the agar and talked about how it felt weird and if it smelled, which indicates that this material was simply an artefact for the students.

In the following process of using vinegar, measuring cups, knives and rulers, the students developed techniques to work with the agar blocks in a way that made sense for the experiment of studying diffusion in cells. The first activities of the experiment were to measure and cut the agar blocks into the right sizes as well as to measure the diffusion and calculate the percentage of the volume that had changed colour were at this point. These activities all included techniques of pragmatic value, namely, dealing with the artefact to provide the results of the difference in diffusion between the three cubes. All the groups found that the smallest agar cube had the largest percentage of changed colour. However, this result may not be that interesting in and by itself for the biology content but needed to be elaborated on by why it is so, and what it reveals about cell size.

In the entire experimental activity, the techniques of pragmatic value serve to produce results and to familiarize students with the artefact of the agar. Techniques of epistemic value, in turn, involve in this case to relate the results of the percentage of changed colour to the relation between the surface area and volume of the agar cube, as well as to infer that the results can be transferred to the context of cells, such that it support understanding of the relationship between cell size and the degree of diffusion across the cell membrane. Importantly, the epistemic techniques are dependent on pragmatic techniques, as the latter provide the empirical basis and experiences upon which epistemic reasoning can build. This connection is seen in the students' written reports.

One group wrote that the experiment showed that:

> The larger agar blocks will have a slower diffusion of vinegar, which is related to the fact that in the larger agar blocks, there is a greater distance that the vinegar molecules must move. […] The most favourable block is the smallest, since its surface area is quite large in relation to the volume, which makes it more permeable to the vinegar and thus more effective." (Our translation from Danish)

The excerpt merely reports upon the results of the agar blocks, which refers to many of their techniques with pragmatic value. They concentrate on the sizes of the agar blocks and which of these there is most favourable to obtain the vinegar. Thus, the genesis of agar blocks as models for cells seems omitted at this point. Yet there is still some understanding of how diffusion is related to size and more importantly to the relation between volume and surface area, which is a central point for the experiment. Then later in their discussion they wrote that agar blocks:

> [...] make it possible to measure how far a substance such as colour that can be simulated as a nutrient can penetrate the block, visualizing the effect of diffusion. They are transparent and easy to manage, making it easier to observe and measure how the diffusion proceeds. […] it was probably chosen not to use real cells, as they would be too small and difficult to observe in detail under a microscope without advanced equipment. The agar block is therefore a practical alternative to simulate why diffusion works in cells. (Our translation from Danish)

This reflection indicates techniques of epistemic value connecting the experiment to the biological context of cells, where the agar blocks turned into an instrument like measuring cups, knives, and rulers, for the purpose of carrying out the experiment and to conclude upon the size of cells and their diffusion. Yet, whereas the other instruments only had pragmatic purposes to execute the exercise, the agar block also had an epistemic purpose to explain and investigate the relation between diffusion and cell size. Similar processes of the agar blocks becoming models or instruments for studying cells were seen in the other students' work during the observation and in the written reports. In the empirical example given, it is easier to recognize the instrumentation, i.e., the influence from the artefact and the setup of the exercise on the students, than how the students' own anticipations and expectations shape the artefact. Through the process of cutting the agar block into the right sizes, observing the change of colour, measuring the differences, and calculating the volume of diffusion, the students got familiar with the artefact of the agar, meaning that they could begin to reflect upon the specific artefact in relation to the diffusion in cells, which we see in their written work.

Discussion

The example from the biology class illustrates that the diffusion of the agar blocks becomes a model for understanding the diffusion of cells through the students' instrumental genesis of the agar blocks. The perspective of instrumental genesis can provide a terminology to understand how models can be understood as artefacts in teaching and learning situations in science. The distinction between artefact and instrument emphasizes the epistemic process of dealing with an artefact to understand and investigate the represented scientific phenomenon. The notion of technique can point the attention to the actual use of the artefact, which indicates the two-way influence between the artefact and the user. The analysis indicates that students instrumentalize models by thoroughly working and dealing with them in different ways using both techniques of pragmatic and epistemic values. In the empirical example, the agar is a physical artefact serving as a model in the interaction with the students, illustrating this complex relation between artefacts as models and models as artefacts. Other kinds of models, such as 2-D illustrations, 3-D figures, and animations, also build on simplifications and idealizations, and the students still need to study a model as an artefact before they can apply it in meaningful ways. Therefore, we find that the instrumental approach also may be fruitful in such situations, which of course require further investigation. Yet the analysis with instrumental genesis indicates that students' interactions with models could be a *modelling genesis*. The lengthy and complex process of instrumental genesis may imply that the genesis of a scientific model as a learning tool also is a complex process, which should be considered when presenting models in science teaching. Moreover, in mathematics education instrumented techniques often have merely pragmatic value and no epistemic value (Artigue, 2002). This is not necessarily the case for the application of models as artefacts but may indicate that the distinction is fruitful when considering for what purposes

certain models are introduced. The transfer of the instrumental approach from mathematics to biology or broader science education remains underexplored, particularly with respect to how the notion of techniques can be meaningfully reinterpreted in relation to science models and practices. Based on the analysis and discussion, we find that it may be interesting to investigate further to what extent knowledge of instrumental genesis is transferable for studying students' modelling genesis.

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Conceptual And Methodological Distortion In Pseudoscientific Theories: How Do Undergraduate Students Recognise These Problems?

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Pseudoscience is an issue that is widely disseminated in society. Its strategies involve mimicking elements of the sciences, but they can present various problems of reasoning. Thus, we aimed to analyse the understanding of undergraduate students in Biological Sciences about the conceptual and methodological distortions presented in the following pseudoscientific constructs: Flat Earth (FL); Intelligent Design (ID); Blood Type Diet (BD); Epigenetic Modulation to Eradicate Diseases (EM); and Homeopathy (HO). The information analysed was collected from an activity developed with 51 students on the Biological Sciences degree course at a Brazilian public university. From our analysis, we identified that the students recognized conceptual distortions in pseudoscientific statements as a type of concept parameters alteration or concept emptying. With regard to methodological distortions, they identified the use of a method unsuited to the issue and the inability of pseudoscientific practices to provide scientific proof. Furthermore, we observed that even though the students brought up other problems with pseudoscience reasoning, they focused mainly on the conceptual or methodological ones. We would argue that in order to understand pseudoscience, science education that considers science as a social practice should be provided, as this would help people to understand science as a social practice.

Keywords: Qualitative Research, Pre-service Teacher Education, Science Education, Undergraduate Learning.

Introduction

Pseudoscience's acceptance is strongly related to one's distorted conceptions of science and scientific activity, and, as both teachers and students have shown these types of distorted conceptions, there is an urgent need to raise discussions on the subject (Rodrigues et al., 2019).

Authors such as Shermer (2011) and Pilati (2018) describe that pseudosciences generally seek to mimic characteristics of scientific practice. It is common, for example, for these pseudosciences to distort scientific theories or present methodological processes that are inconsistent with their claims.

The growing presence of pseudoscientific discourses in media and everyday life reinforces the importance of developing critical scientific literacy among students. When individuals lack a clear understanding of how scientific knowledge is produced, validated, and communicated, they may become more susceptible to accepting claims that superficially resemble science but lack empirical and methodological rigor. Therefore, fostering critical analysis skills becomes a central objective of science education, enabling students to evaluate evidence, recognize fallacies, and question unfounded assertions.

Another point regarding pseudoscience is the discussion about the need to establish criteria for demarcating science from pseudoscience. For Fasce and Picó (2018), it is essential to define such criteria. However, some criteria may not be sufficient for the desired differentiation, since there are multiple areas of knowledge within the sciences themselves, with diverse methodological issues and internal processes that are receptive to criticism, making a "universal" demarcation unfeasible.

In this sense, Olivé (2004) argues that demarcating the boundaries between science and pseudoscience is not a simple matter and involves aspects that go beyond the methodological characteristics of the sciences. From this perspective, he also argues that it is not necessary to categorically demarcate science and pseudoscience, but rather to provide the population with elements to understand pseudoscience based on the philosophical, epistemological and sociological aspects related to its propositions.

From this perspective, rethinking science teaching to make science explicit as a social practice (Longino, 2002) can offer tools for a better understanding of both science and pseudoscience. Considering these discussions, this work aims to analyse the understanding of undergraduate students in Biological Sciences about the conceptual and methodological distortions presented in pseudoscientific constructions.

Methodology

This paper presents a qualitative research (Erickson, 2012) that aimed to analyse the activities carried out by fifty-one students from the Biological Sciences degree course at a public university in the state of São Paulo, Brazil. The activity was carried out in groups of up to five people, totalling 20 groups. Each group received a text with statements that supported and statements that refuted one of the following five pseudosciences: Flat Earth (FL); Intelligent Design (ID); Blood Type Diet (BD); Epigenetic Modulation to Eradicate Diseases (EM); and Homeopathy (HO) (Fasce & Picó, 2018). Thus, each pseudoscience was analysed by four groups. The groups were instructed to identify the main reasoning problems contained in the claims that supported the pseudoscience. We selected the groups that, in addition to identifying the reasoning problem, justified their response, totalling 16 groups. From this organization and selection, our categories of analysis emerged.

Although there were other reasoning problems related to pseudoscience, such as the use of authorities from outside the domain of science or from another area, the focus of this analysis was on the "conceptual distortion" reasoning problem, defined in the activity as the "appropriation of an existing concept in the wrong way, use of valid theories and knowledge to give the impression of veracity, However, the concepts are misrepresented, either by emptying the concept or by altering some fundamental parameters" and "methodological distortion" described as "using a method that is inappropriate to the problem and does not provide credible answers", as these were the reasoning problems most identified by the groups.

As a data analysis methodology, each author of the study, based on the theoretical framework selected in the construction of this study, identified the elements in the responses of the student groups. Subsequently, in a collective meeting, the authors evaluated the classifications made and validated the analyses, proposing a consensus among the categories that will be presented in the discussion section of the results.

Results And Discussion

In this work, we have analysed all the answers prepared by the 16 selected groups, and although the problems of conceptual distortion and methodological distortion occur in all the pseudoscientific practices listed, considering the length of this work, we have chosen to present only a few examples to illustrate our results.

Regarding the student groups' responses to conceptual distortion, the answers were organized into two categories: Fundamental concept parameters alteration; and Concept emptying.

Of the 16 groups, 8 characterized conceptual distortion as fundamental concept parameters alteration, so passages were included that indicate that pseudoscientific constructions mimic scientific concepts that already exist in the sciences in order to induce veracity.

In the case of ID, a conceptual distortion would be to state that mutations, which are key aspects of the Synthetic Theory of Selection, are deleterious and do not generate major evolutionary innovations, i.e. the innovation would result from the increase in the number of bases in the DNA sequence. Group 9's answer describes that the conceptual distortion comes from the fact that the ID considers mutation only as a deleterious characteristic.

> “They use concepts in an incomplete way, [mutations] can be deleterious, but they can also not be.” (Group 9’s response to ID).

The random changes (mutations) generally damage the genetic code, but there is a possibility that these mutations can contribute to innovative or improved biomolecular functioning, even if there is no clarity on the fitness gains that each evolutionary step (mutation) can bring.

The text mentions that “the dilution (of the homeopathic remedy) generally follows a scale, such as the decimal scale (1 : 10) or the centesimal scale (1 : 100), where each dilution stage is accompanied by succussion to potentiate the remedy effect”. Commonly used in laboratory areas, succussion (agitation) is a concept to describe the process of stirring to homogenize a mixture, a standard process in the production of various medicines. Group 6 was able to identify the conceptual distortion presented in the statements:

> “It uses the concept of vigorous agitation as an enhancer of a state of agitation of the molecules.” (Group 6's response to HO).

For Goldacre (2015), this statement is an attempt to associate with pre-existing scientific concepts, so when students signal this term, they recognize a false relationship between the concept and its real application.

Of the 16 groups, 8 characterize the conceptual distortion as Emptying the concept, including passages that indicate pseudo-scientific constructions that cite an accepted scientific concept but completely change its meaning. BD uses the concept of the ABO blood group system to propose dietary adjustments for individuals based on the premise of ancestral genetic inheritance (Cusack et al., 2013). As highlighted by the groups, the claims of this pseudoscience are not supported, as there is no relationship between blood type and the indication of the best “diet” for healthy individuals.

> "[...] each blood type carries information about the behaviour of our ancestors [...]. Weight loss would be associated with a reduction in the consumption of ultra-processed foods and an increase in the consumption of fruit and vegetables" (Group 11's response to BD).

The strategy adopted by BD of using the concept as scientific jargon with the intention of inducing a more scientific language, according to Pilati (2018) and Shermer (2011), is quite common in pseudosciences. Something similar occurs in EM, in which it is claimed that it is possible to modulate genes through food in order to eliminate diseases in their descendants.

> "The idea of a healthy diet, because it's known that healthy diets prevent diseases" (Group 9's response to EM)

Therefore, the claim that "changing our diet can lead to a global reprogramming of the chemical signals that reach our cells and activate (or deactivate) our genes" is an understatement of what epigenetic modulation really is.

In relation to the responses from the 16 groups, only 13 of them identified methodological distortion. The answers were organized into two categories: Use of a method unsuited to the problem, identified by 9 groups; and Inability to provide scientific proof, identified by 4 groups.

Thus, the category Use of a method unsuited to the problem included responses justifying the reasons why a particular method was not sufficient to support the pseudoscientific claims.

In the case of HO, the groups signalled that although they follow some tests to publish their results, they often ignore important steps with the control groups to understand the efficacy of their drugs.

> "The work done (on homeopathy) that corroborates this is not distinguishable from the placebo effect, so there are no methodological criteria that allow the questions asked to be answered." (Group 6's response to HO)

According to Goldacre (2015), homeopathy does not use publicly recognized standards to prove the results of its medicines and is also opposed to these allopathic processes. Thus, when they call a homeopathic medicine effective, they are unable to differentiate its results from the well-known placebo effect.

In the Inability to provide scientific proof category, the discussion on ID came up. This pseudo-scientific practice has created a method to justify the action of "higher forces" to create more complex organisms.

The concept of Specific Complexity is considered by its creators to be a tool for probabilistically identifying signs of ID. It is therefore possible to demonstrate the inability of evolutionary mechanisms to select or generate highly complex systems, inferring that there is design (superior forces).

> "The concept of specific complexity. They create it (specific complexity) as a method to validate what they themselves say" (Group 10's response to ID)

Although group 10 did not delve into the specifics of pseudoscience, they recognized that the specific complexity (superior force) is not verifiable, and was only developed to validate the claims made by the ID.

Similarly, Shermer (2011) describes that although it is the practice of the sciences to propose new methodologies, these new methodological proposals need to be validated by scientific communities, something that pseudosciences don't do.

Conclusion

Based on the research's analysis, we observed that conceptual distortions were understood by these students as a process of fundamental concept parameters alteration or as concept emptying. In addition, when they analysed the methodological distortions presented by pseudoscientific practices, they identified the use of a method that was inappropriate to the problem proposed by these practices or the inability to provide scientific proof based on the method chosen by a given pseudoscience.

Student groups' interpretations indicate that it is possible to discuss epistemological aspects of pseudosciences without necessarily creating universal demarcation criteria, as proposed by Olivé (2000). We observed that even though they brought up other aspects, the students focused mainly on conceptual or methodological ones. In addition, we infer that the focus given to concepts during school and university training could make this aspect closer to the students' reality, and therefore easier to analyse. Something similar may have occurred as a methodological distortion, since these aspects are normally associated with compulsory subjects in the curricula of Biological Sciences courses in Brazil.

Thus, we believe that our activity gave students the opportunity to analyse other reasoning problems that explore epistemological elements of science. Therefore, we advocate providing science education that considers science as a social practice (Longino, 2002), as this would help people understand the epistemological, philosophical and social elements that surround the processes of science construction, which would help them identify pseudo-scientific constructions in society.

Finally, it should be noted that, as this is a qualitative study, our results refer to the class analysed and may serve as a parameter for future discussions on pseudoscience, such as the psychological and social reasons that lead people to believe in pseudoscientific practices.

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Part 2 / Strand 2

Learning Science: Cognitive, Affective, Aesthetic, And Social Aspects

Co-editors: *Regina Soobard & Radu Bogdan Toma*

Part 2 / Strand 2 Learning Science: Cognitive, Affective, Aesthetic, And Social Aspects

Science learning from multi-facet dimensions that go beyond conceptual understanding. Theories, models, methodologies, and empirical results about the cognitive, affective, aesthetics and social dimensions in learning science; design of learning environments; studies of learning processes concerning cognitive, affective, aesthetic and social engagement of scientific contents; forms of representational languages and knowledge organisation, including methods of collaborative construction of knowledge.

Sub-themes:

1) The Role of Emotions in Science Learning and Teaching
2) Developing and Validating Instruments for Measuring Affective Construct
3) Interventions to Enhance Motivation and Interest in Science
4) Theoretical Perspectives on Attitudes and Beliefs in Science Education

Contents

Strand 2: Learning Science: Cognitive, Affective, Aesthetic, And Social Aspects 80

Factors Influencing The Aesthetic Appreciation Of Biodiversity: An Exploratory Study With Pre-Service Teachers 82

Theories Of Intelligence And How They Depend On Students' Definition Of Intelligence 87

Enhancing Students' Interest And Self-Efficacy In Science Through A Large-Scale Teaching Program 93

Enhancing Students' Interest In Chemistry Through Authentic Contexts 98

Using The Four-Quadrant Model To Examine The Character And Value Development Of Pre-Service Primary Teachers About Global Warming 108

Technology Blindness: The Loss Of Affinity And Awareness For Technology 113

Species Portraits As A Means Of Crossing Boundaries To Other Life Forms 121

Detect, Define And Visualize Epistemic Emotions For Science Education 126

Strand 2: Learning Science: Cognitive, Affective, Aesthetic, And Social Aspects

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Reclaiming Attention To Attitudinal Dimensions In Science Education

Strand 2 focuses on science learning as a multidimensional endeavour extending beyond conceptual understanding. Research in this strand examines how learners think, feel, value, experience, and interact while engaging with science-related issues. It brings together theoretical, methodological, and empirical work addressing the *cognitive, affective, aesthetic*, and *social dimensions* of science learning, while building on the longstanding tradition of attitudinal research in science education. Indeed, research within the strand draws on cognitive science, educational psychology, and the sociology of education. The contributions included in this volume reflect the breadth of research represented within the strand. Collectively, they demonstrate that learners' interests, emotions, values, identities, aesthetic experiences, and social interactions are integral components of engagement with science.

Across different educational levels and countries, including Spain, Germany, Denmark, Turkey, and Italy, the contributions explore how these dimensions shape learning processes and how educational interventions can support more meaningful and sustained participation in science. Learning is examined in diverse settings, including classrooms, out-of-school laboratories, natural environments, and collaborative educational programmes and interventions. *Authenticity* emerges as a particularly important aspect of science education. Learning environments that connect scientific ideas to real-world contexts, societal challenges, or personally meaningful experiences are shown to support engagement and participation. This emphasis on authenticity aligns with broader efforts in science education research to bridge the gap between *school science* and learners' *lived experiences*.

A prominent theme across the contributions concerns the *affective dimensions of science learning*. Several studies investigate factors that influence learners' interest, motivation, self-efficacy, and beliefs about learning. These papers address the longstanding challenge of maintaining and strengthening learners' engagement with science across educational stages. They highlight the importance of designing learning experiences that connect scientific content to learners' interests, experiences, and perceptions of relevance. The findings suggest that affective factors are central to participation, persistence, and achievement in science learning.

Another significant theme is *the role of emotions in scientific thinking and inquiry*. The contributions extend affective research by examining epistemic emotions associated with knowledge construction, problem solving, and scientific discovery. This focus reflects growing recognition that emotions are closely intertwined with cognitive processes. Curiosity, surprise, uncertainty, satisfaction, and other epistemic emotions influence how learners engage with scientific questions, evaluate evidence, and construct explanations. The development of analytical tools for identifying and visualising such emotions also points to emerging methodological innovations in this area of research.

A further theme concerns the *aesthetic dimensions of science education*. While aesthetic engagement has received less attention than affective outcomes, several contributions highlight

the potential of sensory and experiential forms of engagement with science-related issues to strengthen learners' connections with science. These include supporting appreciation of biodiversity and encouraging reflection on relationships between humans and other living beings.

Taken together, the contributions in this strand present science learning as a complex process involving cognition, emotion, aesthetics, values, identity, and social participation. As a whole, the volume advances understanding of science learning beyond narrow cognitive perspectives. The contributions offer valuable insights into how science education can support learners in engaging meaningfully and responsibly with science in contemporary society. Therefore, the strand *Learning Science: Cognitive, Affective, Aesthetic, and Social Aspects* is well positioned to contribute to ongoing discussions about the future directions of science education research.

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Factors Influencing The Aesthetic Appreciation Of Biodiversity: An Exploratory Study With Pre-Service Teachers

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The present study aimed to explore the factors influencing the aesthetic appreciation of landscapes with relevant biodiversity, emphasizing the role of scientific knowledge. To achieve this, a questionnaire was administered to a group of pre-service teachers of a Portuguese institution. Participants were asked to rate their preferences for four landscapes with different biodiversity using a Likert scale and to provide justifications for their choices. Two landscapes featured native vegetation, while the other two included exotic and invasive vegetation. The teachers were divided into two groups, with only one group participating in a session focused on the scientific exploration of the landscapes prior to completing the questionnaire. The results showed that the group attending the session demonstrated a greater preference for landscapes with native vegetation, more frequently using scientific arguments to justify their aesthetic appreciation. Nevertheless, other important factors influencing landscape appreciation were identified, such as the presence of specific characteristics of the species and the participants' familiarity with the presented landscapes. Thus, deepening scientific knowledge about biodiversity and engaging directly with landscapes appear to positively influence participants' preferences. The link between higher aesthetic appreciation and the desire for nature preservation seems plausible, although further research is needed.

Keywords: Aesthetic Appreciation, Biodiversity, Pre-service teachers

Introduction

Recent research has increasingly highlighted the emotional and perceptual benefits associated with natural environments. Empirical evidence suggests that natural landscapes, particularly those with minimal human interference, tend to elicit stronger emotional responses (Bethermy & Corraliza, 2019). Within landscapes, specific environmental features play a decisive role in determining preferences, as the presence of water and vegetation is consistently associated with higher levels of appreciation, whereas predominantly sandy or rocky environments tend to receive lower preference ratings (Corraliza, de Frutos & Moll, 2023).

According to Tieskens *et al.* (2017), nearly all rural areas in Europe have been shaped or modified by human activity and can be regarded as cultural landscapes, many of which are now recognized as cultural heritage, indicating that the concept of a "natural landscape" scarcely exists outside a few highly restricted areas. Even in ostensibly natural landscapes, the presence of exotic species is common, further demonstrating that the "human touch" is nearly ubiquitous.

Understanding the factors that influence the aesthetic appreciation of biodiversity can be relevant to uncovering the reasons that motivate people to act in favour of nature preservation. This knowledge can also be valuable for both pre-service and in-service teachers, as it can assist in defining strategies to foster positive attitudes toward nature among students.

According to Carlson (2009), there are two forms of aesthetic appreciation, regardless of the object in question. One of them can be referred to as "free beauty," where the individual simply appreciates the object based on its formal characteristics. The other form, known as "dependent beauty," assumes that knowledge about the object is fundamental to its appreciation. This second

form, although controversial in the field of aesthetics, is particularly relevant to science education, as it links the appreciation of a natural object to the scientific knowledge one has about it.

This perspective, supported by diverse authors such as Frank Muir, Aldo Leopold, and Holmes Rolston, all leading figures in the field of environmentalism, is based on the following principle: the more we know, the more we can observe, admire, appreciate, and ultimately, strive to preserve. As Rolston III (1995) explains, this knowledge allows one to find beauty where it was not previously perceived: "when you understand the harshness of an arid or an alpine climate, you will find the plants' clinging to life aesthetically stimulating" (p. 378).

For this reason, Thompson (1995) argues that the appreciation of nature cannot rely solely on subjective elements but must also include objective elements that underpin this appreciation. From this perspective, the aesthetic appreciation of nature requires scientific knowledge, particularly in fields such as geology, biology, and ecology. This knowledge can also help put destructive events, such as fires, into perspective. According to Brady and Prior (2020), understanding their importance to forest ecology allows us to recognize the value of something that was previously seen only as a force of destruction, turning vibrant landscapes into desolate ones.

The Present Study Area

The present study involved pre-service teachers from a higher education institution in the Lisbon metropolitan area, Portugal. It aimed to achieve the following objectives:

1. To identify the factors that may influence the aesthetic appreciation of landscapes with diverse biodiversity elements.

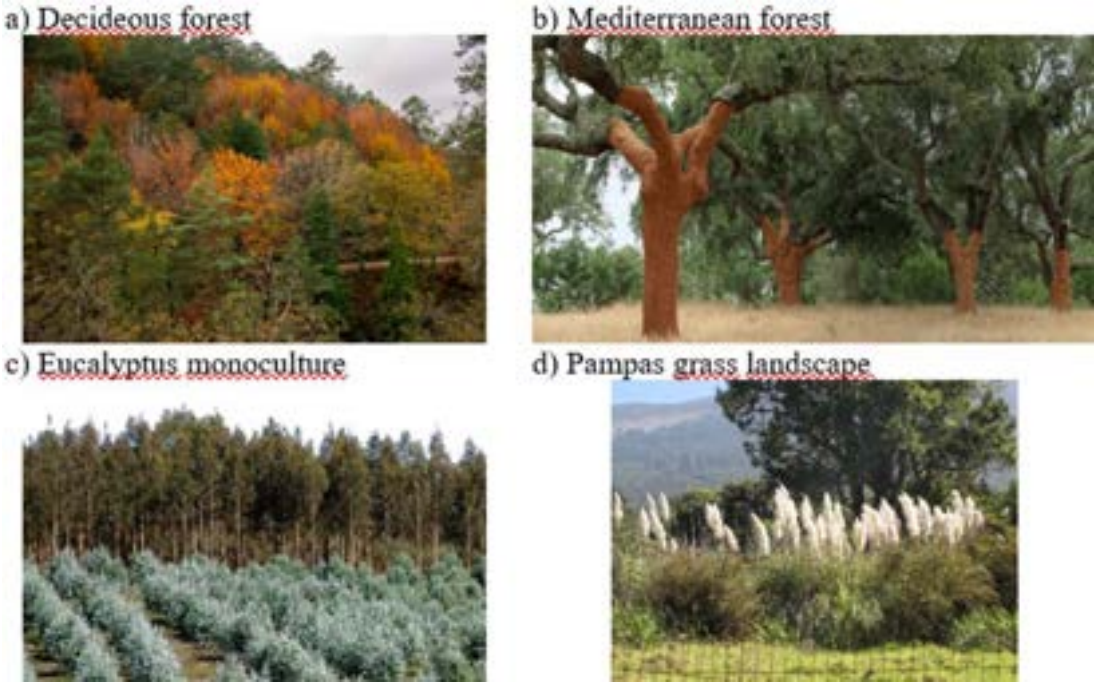
2. To examine the influence of scientific knowledge on the appreciation of landscapes and of the biodiversity elements they contain.

3. To discuss strategies that enhance the aesthetic appreciation of nature, which may prove significant in motivating for its preservation.

Methodology

The present study had an exploratory nature due to the lack of similar research at least in Portugal. A total of 93 pre-service teachers participated (83 – 89.2% female), all enrolled in primary education training courses (master's degree), with a mean age of 23.9 years (SD = 6.067). The data collection instrument was a questionnaire that, in addition to sociodemographic information, presented four photographs of landscapes with varying biodiversity characteristics. Two of the photos featured native Portuguese vegetation: a) A deciduous forest typical of northern Portugal, minimally affected by human intervention; b) A Mediterranean forest (known as *dehesa* or *montado* in Portuguese), a centuries-old human-shaped landscape where nature is sustainably managed. The other two photos depicted exotic and invasive vegetation: c) A eucalyptus monoculture, a tree from Australia that depletes the soil and prevents the establishment of other plant species. Despite these negative impacts, it is widely cultivated due to its rapid growth and is used for paper pulp and timber in the construction industry; d) A landscape dominated by pampas grass (*Cortaderia selloana*), a plant from South America introduced for ornamental purposes that has become invasive due to its rapid propagation (Figure 1).

Figure 1. The four landscapes (a,b,c and d) appreciated by the pre-service teachers.



After the presentation of each photo, the questionnaire included the following questions: 1. According to your preference, rate this landscape on a scale of 1 to 5, where 1 means "I do not like it" and 5 means "I like it very much"; 2. Justify your answer. The questionnaire was validated by two experts in Didactics of Science and considered appropriate for the outlined objectives. The students were randomly divided into two groups (G1 = 48 and G2 = 45), and all completed the questionnaire. However, the students in G2 participated in a prior 45-minute session during which the landscapes were analysed from a scientific perspective. In this session, the main species present in each photo were identified, along with their classification as native or exotic. Additionally, the positive and negative impacts of these species on ecosystems and humans were analysed. For each landscape, the median and mean values of the preference ratings were calculated for each group. To determine if the differences in appreciation were statistically significant, the Mann-Whitney U test was applied with a significance level of 0.05. The justifications provided by the students were subjected to content analysis and categorized according to the nature of the reasons given. The incidence of the different reasons across the two groups was counted and presented in percentages.

Results

The degree of preference expressed for each landscape by each group (median, mean, and standard deviation) is summarized in Table 1, along with the verification of statistically significant differences.

Table 1. The appreciation of the four landscapes by the two groups of participants.

	Median		Mean		SD		
	G1	G2	G1	G2	G1	G2	*p.*
Landscape 1 - Decideous forest	4	5	3.97	4.40	0.956	0.914	0.01
Landscape 2 - Mediterranean forest	3	4	3.14	3.73	1.110	1.268	0.01
Landscape 3 - Eucalyptus monoculture	3	3	3.16	2.73	0.974	1.175	0.04
Landscape 4 - Pampas grass landscape	4	3	3.68	3.26	1.013	1.213	0.09

The results show that participants in G2, who attended the scientific session on landscape analysis, exhibited a stronger preference for landscapes dominated by native vegetation than those featuring exotic and invasive species. The differences between the groups were statistically significant for three of the four landscapes. The exception was the landscape dominated by pampas grass, which still received a higher median score (four, instead of three) in the group that did not attend the session.

The analysis of the participants' justifications from both groups is presented briefly due to space constraints. For Landscape 1 (Deciduous Forest), the responses were predominantly positive. The variety of colours in the landscape was the most frequently cited reason for landscape appreciation by participants in both groups (G1: 72.9%; G2: 57.8%). Additionally, several participants in G2 noted that it represented an ecosystem with native vegetation of high biodiversity (27.9%). The few negative justifications highlighted only one issue: one participant from each group mentioned the excessive vegetation density.

While predominantly positively appraised, Landscape 2 (Mediterranean Forest) also elicited some negative aspects from the participants. Significantly, 20% of G2 participants emphasized the integration of natural and cultural elements within the landscape, a perspective not expressed by G1 participants. The familiarity of the landscape was mentioned by participants from both groups (G1: 8.3%; G2: 20%). In G1, 16.6% of respondents identified the cork oak (Quercus suber) as a beautiful tree, whereas 11.1% of G2 participants emphasized the tree's tolerance of other species. Negative aspects were more prominent in G1, where 20.8% of the participants stated that stripping the tree of its bark reduced its beauty, and 18.8% considered the landscape ordinary. Interestingly, no G2 participant deemed the cork oak's debarking process as negative. This may be because in the session it was highlighted that cork harvesting is a key factor in the preservation of this species in Portugal.

Landscape 3 (Eucalyptus monoculture) received the most negative appreciations, especially from G2 participants. Among G2 respondents, 35.6% pointed out that eucalyptus is an invasive species that depletes resources (soil and water) and is highly flammable, reasons mentioned by only 4.2% of G1 participants. In G1, 29.6% described the landscape as monotonous with little colour variation. Positive justifications highlighted the symmetry in the arrangement of the trees in both groups (G1: 4.2%; G2: 11.1%), with an additional 10.4% of G1 participants noting that the landscape conveyed tranquillity.

Landscape 4 (Pampas grass landscape) garnered more positive than negative assessments from both groups, with this trend being more evident among participants in G1. In G1, 22.9% highlighted the beauty of the pampas grass, a justification also noted in G2 (13.3%). Both groups appreciated the variety in the landscape (G1: 16.7%; G2: 11.1%). Negative justifications were primarily provided by G2, which pointed to the presence of an invasive species (20%) or mentioned its toxicity (4.4%).

Discussion And Conclusions

The study findings demonstrate that scientific exploration of landscape characteristics significantly enhances their aesthetic appreciation. Differentiating between native, exotic, and invasive species, coupled with understanding their ecological and human impacts, proved highly influential. Consequently, this research underscores the crucial role of scientific knowledge in appreciating landscapes and emphasizes the need for a deeper understanding of natural aspects within both classroom settings and outdoor experiences.

Nevertheless, this knowledge is not the only factor contributing to such appreciation. The features of the observed species, referred to as "free beauty" in the introduction section, also played a role

and seem to explain the high appreciation of pampas grass by both groups, though more markedly in the group that did not experience the scientific exploration of landscapes. In essence, the aesthetic appeal of this invasive species seems to somewhat diminish its perceived negative impacts. Therefore, future educational exploration of the present issue should place greater emphasis on the detrimental consequences of this species.

Experiential factors exert both positive and negative influences on landscape appreciation. Familiarity, when associated with positive past experiences, can significantly enhance appreciation. Conversely, when perceived as excessive and lacking novelty, familiarity can have a detrimental effect. While less frequent, some participants expressed feelings of insecurity in landscapes perceived as visually enclosed, a phenomenon previously documented in other research (Ulrich, 1993; Kirillova *et al.*, 2014). The perception of human intervention in landscapes proved to be a nuanced factor, eliciting both positive and negative responses from participants, with no significant differences between groups. This was exemplified by the presence of some symmetry in the arrangement of eucalyptus trees, which was appreciated differently by individuals.

As stated initially, this study is exploratory in nature, but it appears to confirm the importance of scientific exploration for a more effective appreciation of landscapes and biodiversity in general. This aspect should receive special attention in the training of science teachers. The connection between increased knowledge and the desire to preserve nature requires further and more targeted investigation, but the present study suggests that this relationship may be plausible.

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Theories Of Intelligence And How They Depend On Students' Definition Of Intelligence

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The theory of growth and fixed mindsets provides a framework for understanding how beliefs about intelligence influence learning and academic performance. A growth mindset reflects the belief that intelligence can be developed through effort and persistence, whereas a fixed mindset views intelligence as innate and unalterable. To identify whether individuals have a more growth-oriented or more fixed view, the Theories of Intelligence Scale (Dweck, 2000) is used in most reported studies. This scale contains statements like, "You have a certain amount of intelligence and really can't do much to change it." However, we consider it a limitation that these mindset surveys often ask for students' views on the malleability versus fixedness of intelligence but do not define intelligence itself. The present study investigates how German middle-school students' definitions of intelligence may influence their physics-specific mindset. In addition to the mindset survey, students were asked about their definition of intelligence, and the findings reveal distinct differences that are in line with a similar study by Limeri et al. (2020). Students associating intelligence with knowledge were more likely to agree with growth mindset statements, potentially reflecting the perceived adaptability of knowledge. In contrast, those defining intelligence as ability demonstrated more variability in their mindset responses, suggesting differing perceptions of the fixedness or malleability of abilities. Additionally, reasoning power emerged as the most common definition of intelligence, highlighting its role as a widely recognized yet complex concept within cognitive performance. The study contributes to refining the theoretical understanding of mindsets and supports the need for further exploration of how definitions of intelligence influence the measurement of mindsets and what this implies for measuring and interpreting students' learning attitudes, particularly in subject-specific contexts.

Keywords: Belief Measurement, Educational Psychology, Learning Theories

Motivation

The concept of growth and fixed mindsets provides a framework for understanding how individuals perceive their abilities and potential. These mindsets are grounded in beliefs about the nature of intelligence and abilities, that people hold unconsciously. A fixed mindset is characterized by the belief that intelligence is innate, while a growth mindset reflects the idea that intelligence can be developed through effort and learning. These unconsciously held beliefs can significantly influence students' engagement in learning and show an impact on academic outcomes (Dweck, 2000; Yeager & Dweck, 2020). Success in school is not solely dependent on mindsets, however, students with a fixed mindset tend to give up more easily when faced with difficulties or setbacks. In contrast, students with a growth mindset are more likely to choose challenging tasks (Rege et al., 2021) and exhibit a mastery-oriented behaviour in learning situations (Blackwell et al., 2007). Some studies even show better academic results for students with a growth mindset (Paunesku et al., 2015). In general, a growth mindset can be considered supportive in an academic context.

While the majority of mindset research focuses on beliefs about general intelligence, some studies suggest that mindsets can manifest in specific domains (e. g. Hong et al., 1999). Particularly, in STEM fields, a tendency towards a more fixed view has been reported (Dweck, 2008; Leslie et al., 2015; Rattan et al., 2012), which aligns with similar psychological concepts such as the 'talent habitus' (Archer et al., 2020). However, whether the studies target a general or domain-specific

mindset, they usually inquire about beliefs related to intelligence. Mindset questionnaires typically include items like "You have a certain amount of intelligence and really can't do much to change it" (Dweck, 2000), which assess beliefs about the malleability versus fixedness of intelligence but do not define intelligence itself.

Limeri and colleagues (2020) conducted a study with undergraduate students, analysing their definitions of intelligence in relation to their growth mindset scores. They found a significant difference in students' mindset scores based on a dichotomous definition of intelligence: students who defined intelligence as knowledge were more likely to believe in the incremental nature of intelligence than those who defined it as abilities. This may lead to inaccurate mindset assignments, as students who define intelligence as knowledge might answer growth mindset items affirmatively but not exhibit the behaviour patterns typically associated with such a mindset (Limeri et al., 2020). In another study, researchers compared first year STEM students' answers to the typical mindset questionnaire based on the *Theories of Intelligence Scale* depending on their level of agreement to different definitions of intelligence (Diederich & Spatz, 2024). And Sun et al. (2021) observed differences in surveyed mindset patterns when students referred to the model of fluid or crystalline intelligence. The conclusion is similar: measuring mindset based on the Theories of Intelligence scale may not lead to reliable mindset assessment depending on students' intelligence definition.

This research focuses on domain-specific mindsets in physics with the aim to gain a better understanding of subject-specific beliefs. Therefore, a physics-specific mindset questionnaire has been developed and evaluated. This tool contains items of the *Theories of Intelligence Scale* but also incorporates questions about students' beliefs regarding *Giftedness in Physics* and the impact of *Effort in Physics* on learning success. Using these scales, students can be classified into three mindset types: a physics-specific growth mindset (which supports growth mindset statements related to intelligence, giftedness, and effort in physics), a fixed mindset based on general intelligence beliefs, and a fixed mindset based on giftedness in physics (the belief that physics talent predicts success in learning the subject). Students whose answers do not fit any of the three mindset categories are classified into the mixed mindset type (Goldhorn et al., 2023; Goldhorn et al., 2022). Due to the design of this survey instrument, our physics-specific mindset research does not focus on students' intelligence beliefs alone, but these beliefs remain a key element. The influence of students' definitions of intelligence in this context, however, is still unknown.

Research Method

The data presented here aims to investigate differences in students' physics-specific mindset patterns based on their definition of intelligence and is part of a paper-based growth mindset intervention study with N = 210 participating German middle-school students. Before they got to work on the intervention material, students completed the physics-specific mindset questionnaire (Goldhorn et al., 2023) and were asked to define intelligence. First, they answered a single-choice item with the following options: "Intelligence is the sum of what I know," "Intelligence is what I can do," and "Intelligence is reasoning power." The first two options are based on the study by Limeri et al. (2020), while the option about reasoning power is derived from interview studies conducted during the development of the physics specific mindset questionnaire (Spatz & Goldhorn, 2021). In the second step, students were given the opportunity to write their own definition of intelligence if none of the provided options aligned with their understanding.

Results

To simplify the following report and discussion of the results, the intelligence definitions are categorized as reasoning power, knowledge, and ability. A total of N = 191 students answered

the single-choice item about intelligence: 55 % agreed with the definition of reasoning power, 25 % chose the option ability, and 20 % selected knowledge. For N = 98 students, the intelligence item could be matched with the growth mindset questionnaire.

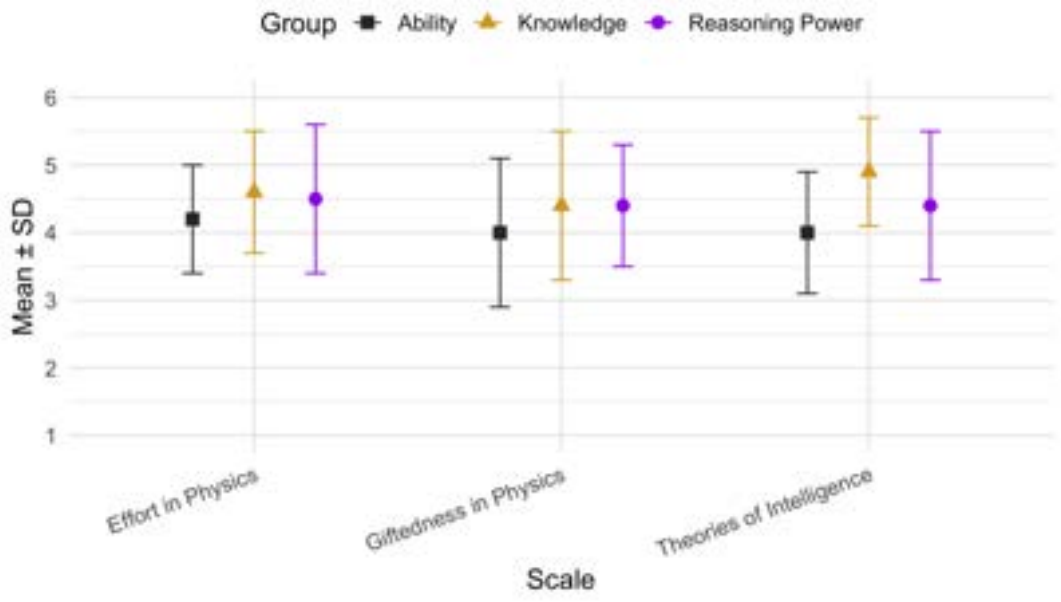
Only the items of the Theories of Intelligence Scale contains the term ‘intelligence’, therefor possible influences of students’ intelligence definitions are expected to appear mainly on this part of the mindset questionnaire. Table 1 presents the mean values and standard deviations for all three scales (Likert scales from 1 to 6, higher values indicating a more growth mindset) that are part of the mindset questionnaire (see Goldhorn et al. (2023) for more details of that mindset questionnaire and the items used). Figure 1 provides an additional visual display on possible group differences based on the mean values and standard deviations.

Table 1: Comparing mean values and standard derivations for each scale of the mindset questionnaire, according to students' intelligence definitions.

Mindset scale / Intelligence definition	Theories of Intelligence ($\boldsymbol{M \pm SD}$)	Giftedness in Physics ($\boldsymbol{M \pm SD}$)	Effort in Physics ($\boldsymbol{M \pm SD}$)
reasoning power	4.4 ±1.1	4.4 ± .9	4.5 ± 1.1
knowledge	**4.9 ± .8**	4.4 ± 1.1	4.6 ± .9
ability	**4.0 ± .9**	4.0 ± 1.1	4.2 ± .8

As expected, a one-way ANOVA reveals a significant effect of students’ intelligence definition, $F(2, 95) = 3.89$, $p = .024$, $\eta^2 = 0.76$ for the *Theories of Intelligence Scale*. Post-hoc comparisons using the Bonferroni correction show that students who define intelligence as knowledge ($M = 4.92$, $SD = .83$) score significantly higher ($p = .002$, $d = .90$) than students who define intelligence as ability ($M = 4.03$, $SD = .95$), i.e. they believe more in the changeability of intelligence. For the other scales, no statistically significant differences can be reported.

Figure 1: Visual display of the mean values and standard deviations of the three scales Effort in Physics, Giftedness in Physics and Theories of Intelligence according to students’ intelligence definitions.



The participating students could also describe intelligence in their own words, and 31 students took that option. Eighteen of them added their own description to their chosen option, for

example, two student who chose *reasoning power* wrote "IQ score" as their own description of intelligence. In general, students' descriptions of intelligence show a broad variety in their perception of intelligence. They include different perspectives from "intelligence is the ability to learn something new and how fast you can learn" to "intelligence means being smart" and "intelligence means how distinctive your brain is".

In our research regarding physics-specific mindsets the mindset questionnaire is used to assign students to different mindset types (see Goldhorn et al. (2023)). To examine possible influences of students' definition of intelligence on those mindset assignments, Table 2 presents the mindset distributions based on students' intelligence definitions. From all N = 98 students, 41 % were assigned to the physics-specific growth mindset, 17 % aligned with the criteria for the fixed mindset 'general intelligence', and 13% identified with the fixed mindset 'giftedness in physics'. The remaining 29% were classified as having a mixed mindset. Slightly more than half of the students who define intelligence as knowledge (53 %) are assigned as holding a growth mindset, while only 24 % of the students who define intelligence as ability are sorted to this mindset group. This difference would support the findings of Limeri et al. (2020) how students' definition of intelligence may shift their mindset assignment, still it is not statistically significant in the presented study.

Table 2: Mindset distribution sorted by students' intelligence definition. Numbers in brackets show the actual numbers of students, N = 98.

Mindset distribution / Intelligence definition	growth mindset (40)	fixed mindset 'general intelligence' (16)	fixed mindset 'giftedness in physics' (14)	mixed mindset (28)
reasoning power (56)	45 % (25)	20 % (11)	9 % (5)	26 % (15)
knowledge (17)	**53 %** (9)	6 % (1)	12 % (2)	29 % (5)
ability (25)	**24 %** (6)	16 % (4)	28 % (7)	32 % (8)

Discussion

Nearly half of the participating students agreed with one of the two concepts of intelligence (knowledge or ability) suggested by Limeri et al. (2020). And sorting students by this dichotomous differentiation of intelligence definition shows a significant difference on how they answered on the *Theories of Intelligence Scale*. The knowledge group is scoring higher (M = 4.92, SD = .83) than the ability group (M = 4.03, SD = .95), which means, these students answer more towards a growth mindset on that part of the mindset questionnaire (see Table 1 and Figure 1). This result aligns with the findings of Limeri et al. (2020). They explained that students who define intelligence as knowledge tend to agree with growth mindset items because it is a common understanding and also the students' experience that knowledge increases over time and can be expanded from any current state. On the other hand, students who define intelligence as abilities show more variation on the mindset scale, depending on whether they view abilities as more fixed or more malleable, which explains more variety on the *Theories of Intelligence Scale* and therefor a lower mean value. Limeri and colleagues conclude that measuring students' mindsets using only the *Theories of Intelligence Scale* might lead to incorrect assignment for those who define intelligence as knowledge. Our sample supports this hypothesis, as the knowledge group scores higher on the theories of intelligence scale and has relatively more students assigned to a physics-specific growth mindset.

The mindset distributions based on students' definition of intelligence (see Table 2) shows differing percentages for the knowledge and the abilities group. Within the knowledge group, there are relatively more students assigned to a growth mindset compared to the abilities group. The student numbers are very small, and the occurring differences are not statistically significant, but they do align with the result about a tendency towards a growth mindset for those students who define intelligence as knowledge. Also, the higher number of students with a *fixed mindset (giftedness in physics)* compared to those with a *fixed mindset (general intelligence)*, especially for students who define intelligence as abilities, supports the findings about a more fixed view of abilities in STEM fields that has been reported by Dweck (2008), Leslie et al. (2015) and Rattan et al. (2012).

The differing scores on the *Theories of Intelligence Scale* related to students' definition of intelligence as knowledge versus intelligence as abilities is the main finding of the presented research. Still, the intelligence definition with the highest level of agreement is reasoning power. This might be equivalent to analytical intelligence and is a very common understanding of intelligence, especially since it aligns with what can be measured in IQ testing (Carpenter et al., 1990). However, there is no specific data on how students really refer to reasoning power and if it is a concept that can be aligned with the mindset theory. From the 31 students who wrote their own description of intelligence the main result is that they show a broad variety and do not refer to a similar concept of intelligence. To clarify students' perception of the word intelligence more qualitative research is needed.

Conclusion

Students' definitions of intelligence seem to influence how they respond to typical mindset statements, such as those found in the *Theories of Intelligence Scale*. In particular, students who define intelligence as knowledge may occur as having a growth mindset, since their perception of intelligence aligns with an incremental concept. But answering the mindset items based on that does not mean they truly believe in an incremental theory of developing one's individual potential. Mindsets are a powerful predictive tool, especially when students can be shifted to a more growth mindset approach to academic learning through mindset interventions. However, to effectively do this, the commonly used instrument with its sole focus on intelligence, should be critically evaluated. Based on our research, domain-specific scales that do not use the term 'intelligence' appear more reliable for identifying students (domain-specific) mindsets and there are no statistically significant differences in a mindset assignment based on all three scales as we propose in our research (Goldhorn et al. (2023)). This finding highlights the importance of using mindset measures that do not focus exclusively on intelligence.

The present study is a small sample, but it supports the hypothesis proposed by Limeri et al. (2020) and Sun et al. (2021): students' definitions of intelligence do matter when investigating mindset and warrant further exploration to ensure all the possibilities regarding mindset research.

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Enhancing Students' Interest And Self-Efficacy In Science Through A Large-Scale Teaching Program

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Globally, a lack of student interest in science education remains a critical challenge, particularly among primary and secondary students. This poses difficulties in fostering scientific literacy and meeting workforce demands for scientific competencies. Existing programs that enhance interest and self-efficacy often lack scalability, requiring significant resources and time commitments from schools and teachers. To address these limitations, a large-scale teaching program was developed with the aim of improving science education. In 2024, over 135,000 students participated in this program. We study one of the teaching units that are part of the program. The teaching unit includes a 1.5-month in-school teaching unit as well as a one-day out-of-school lab activity and is based on an inquiry and Socio-Scientific Issues approach. It aims to increase student interest, engagement, and self-efficacy in science. A quasi-experimental difference-in-differences design evaluated the unit's impact across 1,951 students in 189 classes. The results show medium effects on situational interest (0.64 SD) and students' ability to relate science to societal challenges (0.55 SD). Confidence in mastering content-specific tasks showed large effects (0.98–1.59 SD), though improvements in general motivation and broader scientific competencies were limited. The study shows that it is possible to develop a scalable approach to science education that combines minimal preparation time from teachers with significant improvements in student outcomes. However, the study indicates that a 1.5-month program alone is insufficient to significantly improve students' general motivation for science or develop general scientific competencies. Future impact evaluations will explore different possibilities for improvement.

Keywords: Interest. Self-Efficacy. Student Engagement

Context And Relevance

Students' lack of interest in science education remains a significant global challenge, particularly among primary and secondary school students. The lack of interest in science poses challenges both in terms of motivating and strengthening students' general scientific literacy and in educating enough students with scientific competencies to meet workforce demands (Griethuijsen et al., 2015).

While various educational programs have demonstrated effectiveness in enhancing students' interest and self-efficacy in science, these interventions often face critical limitations: they are resource-intensive, lack scalability, and demand substantial time commitments from schools and teachers. These constraints often result in participation being limited to a small, self-selecting group of motivated educators and schools, making it difficult to generalize findings or achieve widespread impact.

A recently funded program, organized externally from schools, has developed science teaching units to address these barriers. Unlike many traditional programs, this initiative is designed to be scalable and accessible, reducing demands on teachers' time and resources. This model enables broad participation across diverse schools and student populations. In 2024, more than 135,000 students participated in a teaching unit, most of them in middle or lower secondary schools.

As part of the grant, an ambitious impact evaluation strategy has been developed. The first evaluation was conducted on one of the teaching units targeting 9th-grade students. The teaching unit, based on an inquiry-based approach, consists of a 1.5-month in-school activity and a one-day follow-up out-of-school lab event. The evaluation measured effects on 9th-grade students' interest and self-efficacy in science across different student groups, including those traditionally less motivated in science. Evaluating whether a large-scale science program can effectively improve students' interest and self-efficacy in science is crucial for understanding how more students can access high-quality science education.

Research Questions

The research questions are:

1. Can the teaching unit improve students' situational interest and general motivation for science?
2. Can the teaching unit enhance students' content-specific self-efficacy and their self-efficacy in conducting experiments?
3. Are the program's effects consistent across different student demographics and academic backgrounds?
4. What lessons can be drawn about the scalability of high-quality educational interventions?

Theoretical Framework For The Development Of Outcomes

The impact evaluation is based on seven survey scales measuring students' interest and motivation for science, and science self-efficacy. The survey scales were developed and validated following the seven steps recommended by the Association for Medical Education in Europe (Artino et al., 2014). These steps include a thorough literature review of international research, expert validation by science researchers, cognitive interviews with students, and statistical validation. Our scales draw from established science education research and are adapted to a domestic school context. The scales were statistically validated using the Rasch model with pilot data collected in 2023 (Rambøll, 2024).

Situational Interest

Two scales measure students' situational interest in science lessons. These are based on Hidi and Renninger's (2006) four-phase theory of interest development and inspired by Linnenbrink-Garcia et al.'s (2010) Situational Interest Measures survey instrument. The two scales measure the first two phases of the theory. Are students more inclined to participate and more engaged (called Triggered situational interest), and do they find the teaching unit more relatable and meaningful (called Maintained situational interest) than their regular science lessons.

General Motivation For Science

Two scales measure students' broader motivation for science, focusing on intrinsic and extrinsic motivation. These scales are based on Ryan & Deci's (2020) Self-Determination Theory and adapted from validated scales developed by Makransky et al. (2020) students in grades 4–9 in the relevant country.

Content-Specific Self-Efficacy

Two scales measure students' confidence in mastering the specific academic content covered in the teaching unit. The items broadly align with the program's learning objectives and national science curriculum goals. The scales draw on Albert Bandura's (1997) concept of self-efficacy and related studies (e.g., Fidan & Tuncel, 2021).

Self-Efficacy In Conducting Experiments

This scale measures students' self-efficacy in conducting experiments and evaluates whether the teaching unit impacts their more general scientific inquiry skills. The scale is inspired by Hu et al.'s (2022).

Research Method And Data

The impact evaluation employs a robust quasi-experimental difference-in-differences (DiD) design. In the intervention group, students' interest and science self-efficacy are measured both before and after participating in the teaching unit. Similarly, in the control group, students are measured twice within the same timeframe as the intervention group. The effect is calculated as the difference in outcome development between the intervention and control groups. The design employs a kind of 'wait-list' design, where the control group consist of classes that has enrolled but had not yet started the teaching unit. This approach was used to avoid self-selection bias. Pre-scores show no substantial difference between the control- and intervention groups.

The DiD estimator is calculated using a simple regression model (a two-way fixed-effects model): $Yit = \beta i + \beta t + \rho Tit + uit$

where T equals 0 for the control group and 1 for the intervention group, uit represents the unobserved error term, and βi and βt are individual and time fixed effects. The parameter ρ captures the average causal effect of the teaching unit. As a sensitivity analysis, we tested a model that controlled for students' background variables (gender, ethnicity, grades, parental education, and income). The results did not yield substantially different results compared to the simpler model.

The dataset includes 1,951 students across 189 classes, with each student completing the survey twice. The analytical sample does not differ significantly from the entire population of 9th-grade students in the relevant country.

Findings

Figure 1 (next page) shows the results of the impact evaluation.

Improved Interest, Engagement, And Relevance

Students taught in the teaching unit were more interested and showed a greater desire to participate in science lessons compared to students in the control group (Triggered situational interest, medium effect: 0.64 SD). Additionally, students found that the teaching unit, more than regular science lessons, could be related to daily lives (Sustained situational interest, small effect: 0.25 SD). When directly asked if the teaching could be related to societal or global challenges, there was a medium effect (0.55 SD).

Weak Improvement In General Motivation For Science

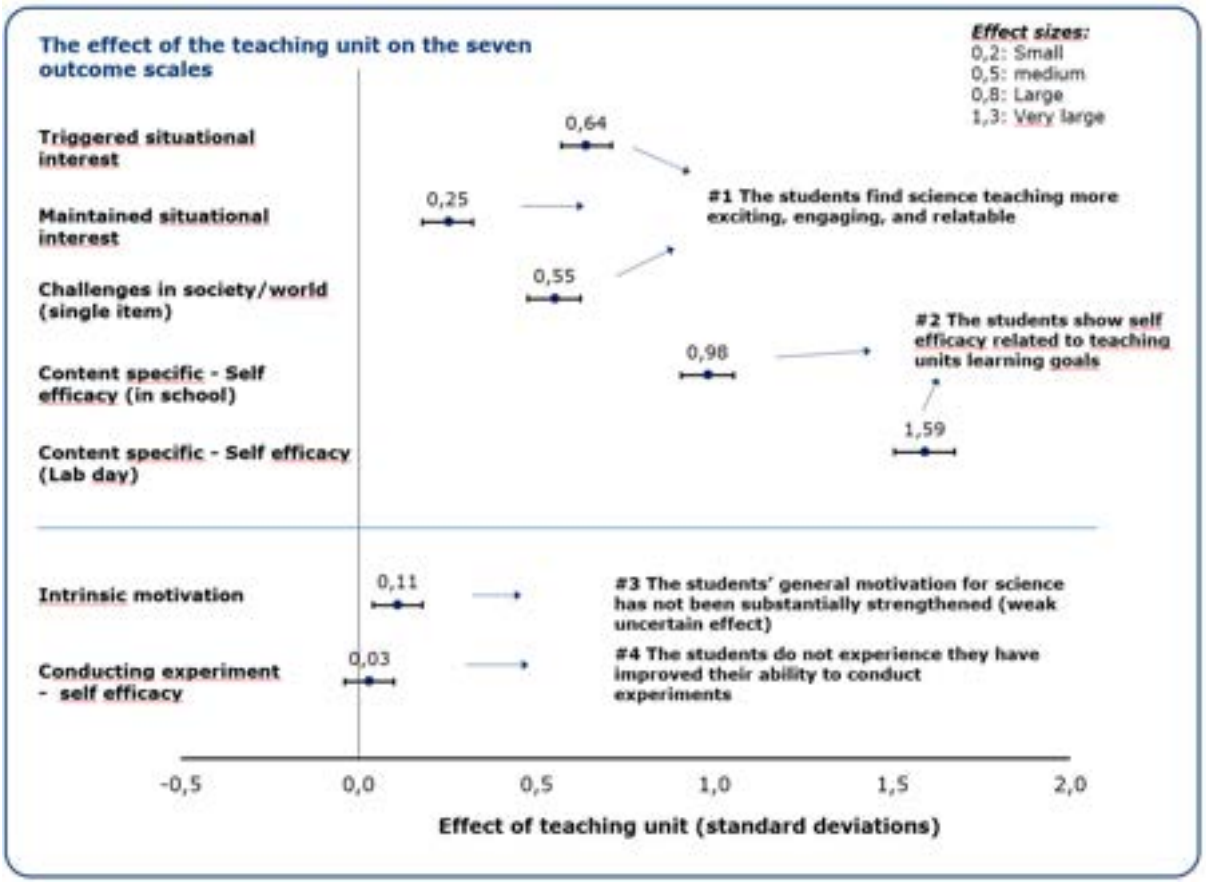
Despite students finding the teaching unit far more engaging and relevant than regular science lessons, it did not substantially enhance their broader motivation for science (Intrinsic motivation, small uncertain effect: 0.11 SD).

Enhanced Content-Specific Self-Efficacy

Students demonstrated greater confidence in their ability to perform science-related tasks, linked to the teaching units learning objectives (Content-specific self-efficacy, large effect: 0.98–1.59 SD). This outcome is not surprising, as the design does not ensure that the control group worked on the same topic as the intervention group. Other effect studies typically show effects on outcomes that relate directly to the teaching units learning goals (Slavin et al., 2014).

Nevertheless, the effect sizes suggest that students generally achieve the nationally established objectives addressed by the program.

Figure 1: Results Of Impact Evaluation. Standardized effect estimates from regression models, with cluster-robust standard errors at the class level. Lines indicate 95% confidence intervals around point estimates (n=3,876 observations). Source: Rambøll, 2024.



Lack Of Improvement In Conducting Experiment Self-Efficacy

Students did not assess they had improved in their ability to conduct experiments. Regarding the development of broader scientific competencies, such as inquiry skills, either the teaching program was not sufficient, or different approaches are needed.

Equity Across Student Groups

Subgroup analyses revealed that the improvements in situational interest applied across various groups, including students of different genders, ethnic backgrounds, academic performance levels, and socioeconomic statuses. However, students with higher initial academic performance showed slightly greater gains in content-specific self-efficacy.

Discussion Of Findings And Implications

The study shows that it is possible to develop a large-scale science program for teachers that requires minimal preparation time and increases students' interest, participation, and engagement in science. This effect was measured on a representative group of schools and students, and the results demonstrate that the increased interest and engagement in science benefited all student groups, including those who traditionally show less interest in science.

The study indicates that a 1.5-month program alone is insufficient to significantly improve students' general motivation for science or develop general scientific competencies. Future impact evaluations will explore whether multiple teaching units can achieve more general and long-term effects, incorporating survey data and registry-based measures such as 9th-grade exam scores and enrolment in science-focused education.

Observations and interviews with students and teachers collected as part of the impact evaluation suggest that some teachers face challenges in implementing its inquiry-based approach (LIFE Fonden, 2024). Exploring whether more direct support for teachers could lead to broader student outcomes is therefore warranted. Such support could improve the program's implementation and potentially enhance teachers' instruction across other science lessons. To address this, a research project is underway to develop teacher support tools that raise awareness of inquiry-based didactics and enable practice of its key elements during the program.

The teaching program exemplifies a scalable approach to science education that combines minimal time investment from teachers with significant improvements in student outcomes. By addressing barriers to participation and achieving broad reach, the program demonstrates the feasibility of providing student access to high-quality educational experiences. This evaluation provides valuable insights into how scalable models can maintain effectiveness while expanding their impact across diverse educational contexts. However, more research is needed to understand what is required to create broader and more lasting effects.

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Enhancing Students' Interest In Chemistry Through Authentic Contexts

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Despite the immense amount of research findings concerning interest and motivation, the successful transfer of these findings into educational practice could be doubted when studies continuously reveal a lack of interest in STEM subjects, especially in chemistry. The authors take the persistent interest deficit as an opportunity to discuss a new way of promoting interest in chemistry based on a combined conceptual framework that draws from various theories connecting interest, authenticity and constructivism. Aiming to create an authentic, context-structured learning environment to enhance situational interest in chemistry, an out-of-school laboratory course for middle school level using authentic medical cases was developed. During the course, students are confronted with an authentic file of a patient after an asthma attack. Drawing on both medical background information and chemical concept knowledge, they conduct different experiments with carbon dioxide and carbonic acid to eventually diagnose the patient with respiratory acidosis. Before the course, individual dispositions and prior situational interest were assessed with a questionnaire. After the course, situational interest was assessed again, as well as the perceived authenticity of the whole course. Analysing the quantitative data of 155 students, indications arose that the relationship between individual interest and situational interest is partially mediated by perceived authenticity. Perceived authenticity is displayed as a crucial factor for potential interest enhancement, especially for learners with low individual interest in chemistry.

Keywords: Interest, Learning Environments, Out-of-School Learning, Authenticity

Introduction

Situational as well as individual interest have been one focus of educational research for over half a century but the transfer of such findings into educational practice could be questioned: Looking at Germany and Austria alone, latest studies show a strongly decreasing gradient from perceived competence, over interest, to the career aspirations in science subjects (SINUS Markt- und Sozialforschung GmbH, 2024). This trend can be found throughout the Western European countries (van Griethuijsen et al., 2015). Chemistry is particularly unpopular. Apart from a shortage of skilled workers in STEM disciplines (Anger et al., 2024), a lack of interest is also problematic for learners who do not aspire a career in science. STEM (here: chemistry) education should therefore not only appeal to future researchers but should also be designed to be attractive to all learners to enable participation in our society and informed everyday decisions (Hüfner et al., 2025). Students often name everyday references and practical knowledge as potentially interesting facets of chemistry (Fleischer et al., 2024; SINUS Markt- und Sozialforschung GmbH, 2024). Yet, these aspects are hardly anchored in (Western European) chemistry curricula, even though various teaching concepts for interest enhancement already exist. Making chemistry more appealing still presents a challenge that needs to be addressed by finding a suitable way to combine approved methods with research findings as well as with the individual learners' views and needs.

Conceptual Framework

Constructivism In Science Lessons

Modern educational systems and educational research are based on the fundamental assumptions of (social) constructivism as the prioritized approach to successful learning. Impactful theories,

such as Situated Cognition, Cognitive Apprenticeship or Anchored Instruction, laid the foundation for our understanding of the conditions for the independent construction of knowledge during learning processes. To enable situated learning and to fight inert knowledge, authentic contexts and activities play a central role (Ghefaili, 2003). It has been well researched that people of all ages tend to neglect the personal relevance of science in their lives (Kantar, 2021). Given that situated learning always relies on creating meaningful learning environments with authentic real-world complexity (Honebein et al., 1993; Ghefaili, 2003), this widespread neglection seems disadvantageous for learning (and liking) science. It has been found that strictly following constructivist design guidelines does not alone make a difference regarding interest in learning situations (Xu et al., 2024; Yeung et al., 2025). It therefore remains to be refined to what extent situated learning, interest and authenticity interact.

Interest And Learning

A stable preference for topics or activities is referred to as individual interest, describing an individual trait. Interest can also show in form of temporary engagement, referred to as situational interest. Individual interest is often seen as the most important predictor of situational interest (Rotgans & Schmidt, 2018), while there is also research describing important "triggers" for situational interest arising from a learning environment (Renninger et al., 2019). The so-called person-object theory of interest (POI) states a bipolar unit of person and situation (Krapp, 1999). Both interest as a personal disposition and interestingness as a feature of learning environments can lead to the psychological state of being interested in something (Krapp et al., 1992). The four-phase model of interest development (FPM) "describes phases of situational and individual interest in terms of both affective and cognitive processes" (Hidi & Renninger, 2006, p. 113), therefore proposing a structured process in which individual interest evolves based on experiencing situational interest. Hidi and Renninger (2006) assume situational interest to be triggered in certain situations with the potential to be maintained through personal relevance of the topics or materials. Both POI and FPM are frequently used as theoretical backgrounds for current research.

Situational interest is composed of an emotional, a value-related, and an epistemic compound, stating that besides experiencing meaningfulness and positive emotions during learning, curiosity and engagement contribute to being interested (Prenzel et al., 1986). Research shows that increased situational interest can lead to more positive affect as well as higher cognitive engagement and therefore contribute to knowledge acquisition through intensifying and maintaining effort (Su, 2020). Research provides scattered results concerning STEM contexts that seem interesting to students (Hoffmann et al., 1998; Sjoberg & Schreiner, 2005) and therefore illustrates that interestingness does not follow universally applicable rules for every individual learner, highlighting the importance of integrating individual perceptions. It is suggested that one context can affect different learners in different ways (Habig et al., 2018; van Vorst & Aydogmus, 2021; Yeung et al., 2025). Some researchers discuss a balance between dispositional and situational (environmental) facets when it comes to enhancing situational interest (Schäfer & Habig, 2024). Such a balance is strongly supported by the constructivist approach that learning equals the behaviour of individuals, bringing their own larger context with them, engaging in a local (learning) environment where tasks are situated (Honebein et al., 1993). Unfortunately, research still provides only limited explanations as to *why* interest develops which way for different learners.

Interest, Authenticity, Contextualization, And Their Link To Constructivism

Chemistry is often perceived difficult or abstract. One reason for low interest in science could be contextualization not fitting highly individual values and preferences. According to the situational

expectancy-value theory (SEVT, Eccles & Wigfield, 2020), low situational interest could be explained by science seeming non-enjoyable and far from useful. As a result, a learning context may be perceived as not compatible with oneself. According to the Person-Environment Fit Theory (PEFT, van Vianen, 2018), only a good alignment between individual characteristics and the (learning) environment leads to engagement and better performance. This fit is therefore directly linked to interest. A similar concept of "fit" is used by Zualkernan (2006). Following this framework for constructivist learning environments, the learner "adapts" to an environment in such a way that she can be "fit" for the tasks in question (Zualkernan, 2006). Especially the "structural fit" seems similar to the PEFT as it describes "how closely the cognitive constraints and learning styles of the learner 'match' to the information present in the environment" (Zualkernan, 2006, p. 200). If complete dissonance occurs, individuals might refuse all information presented in a learning environment. If these models are joined with the concept of authenticity, it could be inferred that a good fit is reflected in a high perception of authenticity before it results in increased (situational) interest.

That is, *perceived* authenticity plays a central role in stimulating and maintaining situational interest (Betz et al., 2016). It has been proven that the *intended* level of authenticity neither had effects on perceived authenticity of the students nor on their situational interest, providing us with the necessity to include the learners' personal views. All components connected to the individual feeling of authenticity have been linked within the Model of Authenticity in Teaching and Learning Contexts, stating that the feeling of authenticity manifests as a product of an individual authentication process which is itself influenced by personal dispositions as well as characteristics of the environment (Betz et al., 2016). Aiming to design authentic learning materials means enabling students to make connections of the learning content to real life (Fougt et al., 2019). *Authentic* has been used extensively, but not consistently, to describe learning situations connected to real life. Shaffer & Resnick (1999) state that different kinds of authenticity may overlap to create "thick" authenticity, a strong perception of authenticity. They include criteria like alignment with the outside world, with a specific discipline, or with what learners really want to know (Shaffer & Resnick, 1999). Other authors suggest various design principles for authentic learning environments, e.g. authentic contexts, expert performance, collaboration or scaffolding (Herrington & Oliver, 2000). Real-world problems, inquiry, discourse among the community of learners as well as empowerment of the learners are seen as components of authentic learning (Rule, 2006). A feeling of relevance and usefulness (in these terms: a feeling of "fit") is supposed to arise when students perceive learning environments as authentic (Nachtigall et al., 2018), making authentic contexts a promising approach to effectively use situated learning for interest enhancement. Yet, findings about what really induces perceived authenticity in the individual learner remain ambiguous, e.g. concerning instruction methods and guidance (Hohrath et al., 2024; Nachtigall & Rummel, 2021).

Aims And Research Questions

Although the theoretical foundation suggests that perceived authenticity has a key role in the constructivist view of situated learning processes concerning the development of situational interest, studies often do not integrate *perceived* authenticity in interest assessments of (context-based) learning environments (Nachtigall et al., 2022, 2024). The individual learner's personal perspective is of ultimate value for determining if constructivist pedagogies reach their goal of presenting fitting situated learning environments because "not only is [the learner] entitled to make judgements about what counts as authentic for her but, in the final analysis, it is her authenticity which really matters" (Splitter, 2009, p. 143). One way to examine such a fit is through authenticity (Betz et al., 2016). Learning materials that are perceived as authentic would

enable students to make credible connections between the learning content and real life (Fougt et al., 2019).

This gives rise to the hypothesis that an increased fit and thus an increased perception of authenticity is a positive starting point for the enhancement of situational interest yet depends on the individual learner. Consequently, the following research questions arise:

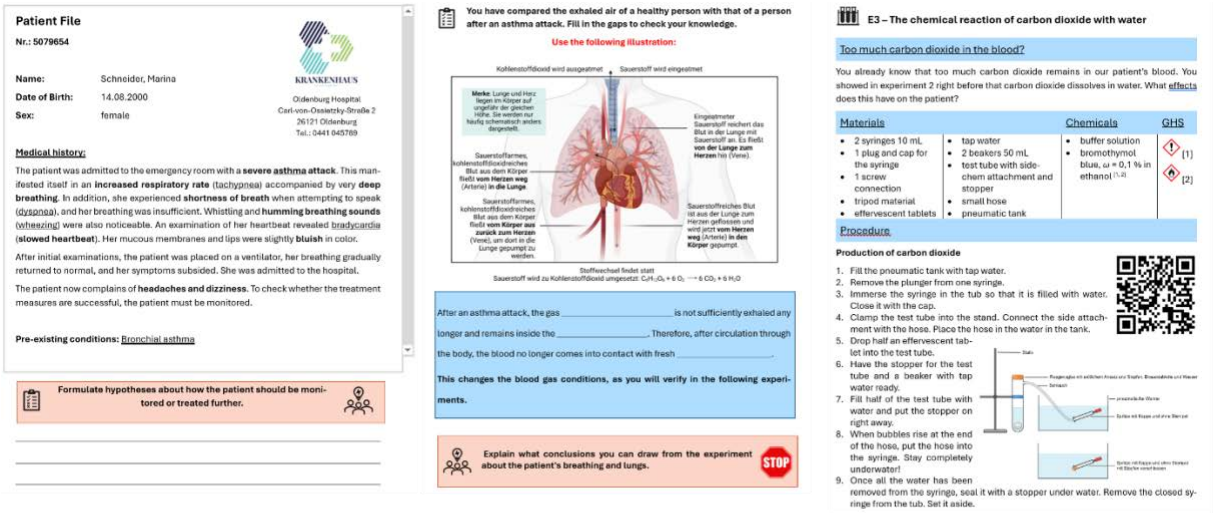
1. How is the perception of authenticity linked with other interest-determining factors?
2. Does our design of a context-based learning environment seem more authentic, or more interesting, to learners with a special set of dispositions?

Research Design And Methods

Designing An Authentic Context-Based Learning Environment

To examine the connections between situational interest, perceived authenticity and individual dispositions in a context-based learning environment, we decided on conducting a survey in an out-of-school student laboratory. Trying to obtain a high level of *intended* thick authenticity in alignment with Shaffer & Resnick, we searched for a context that connects chemical knowledge with problems from the real world, that is aligned with a specific discipline and with topics learners want to know about. Because various studies confirmed young people's universal interest in medical topics (Hoffmann et al., 1998; Sjoberg & Schreiner, 2005), and because chemical concepts are of essential use for medical cases, we picked a medical context. To align our learning environment with real-world problems, we reconstructed an authentic patient's case in collaboration with experts in medicine from the local clinic. As a result, a learning environment using a patient file as contextual structure was designed (see Figure 1).

Figure 2. Exemplary screenshots from the (translated) learning material.



Task: Formulating hypotheses about how the patient should be treated further.

Task: Explaining how an asthma attack influences the respiratory system.

Task: Explaining how an asthma attack influences the blood gas parameters.

The patient file and the respective diagnosis to be made served as the initial problem the students would encounter. Our patient, a young girl with bronchial asthma, came to the hospital after a severe asthma attack, and was administered oxygen. Now, the causes of her ongoing headaches and dizziness following the treatment should be identified. The students start making suggestions for suitable medical examinations and are supported by additional medical information and scaffolding, concluding that a blood gas analysis should be arranged. In the laboratory, they conduct simple and easy chemical experiments to model the steps of a blood gas analysis. Conducting chemical experiments for the detection and quantification of carbon dioxide as well

as the acidic reaction of carbon dioxide in aqueous solutions, the students are guided towards diagnosing the patient with respiratory acidosis as a condition following the severe asthma attack (Boemke et al., 2012).

Survey Instrument And Methods

The three-hour course was accompanied by a questionnaire in a pre-post format (Dietel & Wilke, 2025). To assess dispositions in the pre-test, five and three items on five-point Likert scales were used to measure individual interest in chemistry (*ind(ch)*) and medicine (*ind(med)*). Situational interest was assessed in both the pre- and post-test using five items on a five-point Likert scale (*sit(pre)* and *sit(post)*). In the post-test, perceived authenticity was also assessed using three items (*auth*). Additionally, the students could deliver a short, written statement on why they felt that way about their authenticity perception. Table 1 shows exemplary items with the original sources and the reliability of the scales.

Table 1. Questionnaire Details.

Scale	Exemplary Item (translated)	Source	Cronbach's α
ind(ch) (5 items)	I like working on tasks from chemistry lessons.	Frey et al., 2015; Habig, 2017 (adapted)	.907
ind(med) (3 items)	I enjoy exploring medical topics.	Frey et al., 2015; Habig, 2017 (adapted)	.898
sit(pre) (5 items)	Learning chemistry with this topic will be fun.	Habig, 2017 (adapted)	.863
sit(post) (5 items)	Understanding this topic is important for me.	Habig, 2017 (adapted)	.868
auth (3 items)	I have learned something from everyday life of real people today.	Finger et al., 2022 (adapted)	.792

A correlation analysis was carried out in SPSS. Assumptions concerning mediating effects of different constructs on the development of situational interest were tested using the PROCESS macro by Hayes (Hayes & Little, 2018). Group differences were analysed using ANOVAs.

Findings

The data from 155 students aged 14-16 years were analysed. 79 participants identified as female, 69 as male, and 7 stated another gender. All scales showed good or very good reliability (see Table 1). The participants reported medium-high situational interest in both pre-test (3.61 ± 0.67) and post-test (3.59 ± 0.84) as well as medium-high perceived authenticity after the intervention (3.77 ± 1.06). Individual interest in chemistry (3.05 ± 1.04) was rather low while individual interest in medicine was on a higher level, as expected (3.60 ± 1.11).

To answer the first research question, a correlation analysis as well as mediation analyses were performed. From a correlation analysis (Spearman's rho, see Table 2), it arises that perceived authenticity is correlated with every surveyed construct, and it is especially highly correlated with situational interest in the post-test. Both *ind(ch)* and *ind(med)* are highly correlated with *sit(pre)* as well as with *sit(post)*. Nevertheless, the correlation remains constant (*ind(ch)*) or decreases (*ind(med)*) from pre-test to post-test, while the correlation of *auth* with situational interest increases from pre-test to post-test. This suggests that perceived authenticity became relevant for

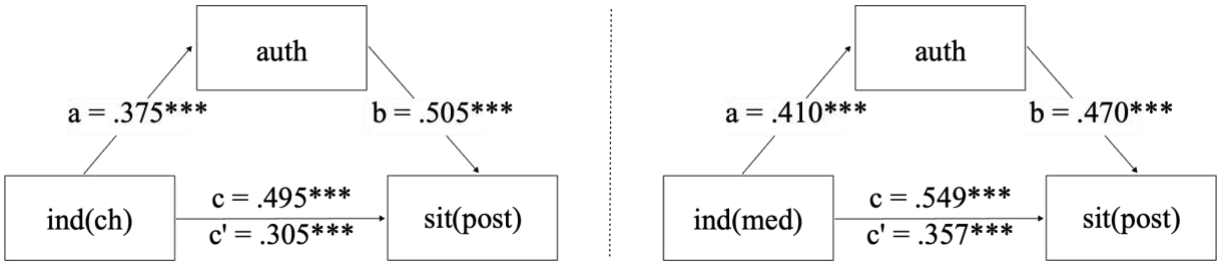
situational interest during the intervention while indicating that the dispositions may play a more foundational, rather than dynamic, role in interest development.

Table 2. Correlation Analysis.

	ind(ch)	**ind(med)**	**sit(pre)**	**sit(post)**
ind(med)	ρ = .300 p < .001			
sit(pre)	ρ = .555 p < .001	ρ = .649 p < .001		
sit(post)	ρ = .555 p < .001	ρ = .593 p < .001	ρ = .701 p < .001	
auth	ρ = .380 p < .001	ρ = .430 p < .001	ρ = .424 p < .001	ρ = .714 p < .001

The correlation analysis prompted a further examination of the initial hypothesis: the central role of perceived authenticity for interest enhancement. This is why the effects of different dispositions on the post-test value of situational interest were checked for a mediating influence of perceived authenticity. All relationships were approximately linear, as assessed by visual inspection of the scatterplots after LOESS smoothing. A simple mediation was performed. An effect of *ind(ch)* on *sit(post)* was observed. After entering perceived authenticity into the model, *ind(ch)* predicted this mediator *auth* significantly, which in turn predicted *sit(post)* significantly. We found that this relationship is partly mediated by *auth*. Also, the effect of *ind(med)* on *sit(post)* was significant and got partly mediated by *auth*. The mediation paths are visualized in Figure 2.

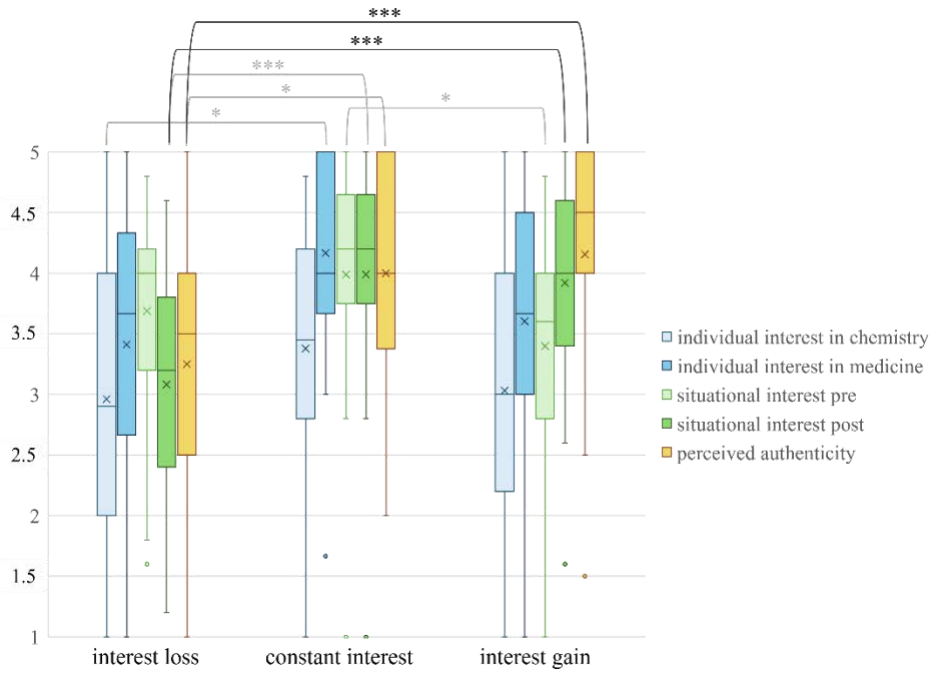
Figure 3. Mediation figures (* - significance p < .001).**



To answer our second research question, we divided the data into three groups according to the development of situational interest from pre-test to post-test. This resulted in the groups "interest gain" (*sit(post)* - *sit(pre)* > 0, N = 71), "interest loss" (*sit(post)* - *sit(pre)* < 0, N = 62), and the group "constant" (*sit(post)* - *sit(pre)* = 0, N = 18). Levene's test revealed equal variance among the groups regarding the constructs *ind(ch)*, *ind(med)*, *sit(pre)* and *sit(post)*. An ANOVA showed significant differences in the areas of *ind(med)*, *sit(pre)* and *sit(post)*. A Tukey test specified that significant differences between the "interest gain"-group and the "interest loss"-group only occurred concerning *sit(post)* ($F(2, 148) = 19.54$, $p < .001$, $\eta^2 = .209$). Other significant differences were found only in comparison to the "constant"-group. For perceived authenticity, variance inequality over the three groups had to be assumed. Here, a Welch-ANOVA followed by a Games-Howell test also revealed significant differences between the "interest gain"-group and the "interest loss"-group ($F(2, 46.25) = 14.42$, $p < .001$, $\eta^2 = .174$). These large effects suggest that, given similar dispositions and similar starting points in terms of situational interest, perceived authenticity is the only factor surveyed here that contributes to divergent interest

development comparing “interest gain” and “interest loss”. Significant differences are visualized in Figure 3.

Figure 4. Boxplots for the group comparison (development of situational interest).



Additionally, data from male and female participants were included to determine gender differences. Levene’s test confirmed the homogeneity of variance between the two groups regarding all constructs. An ANOVA revealed significant differences for *ind(med)* ($F(1, 146) = 12.22$, $p < .001$, $\eta^2 = .077$) well as *auth* ($F(1, 145) = 6.99$, $p = .009$, $\eta^2 = .046$) in favor of girls. For *ind(med)*, the effect ($\eta^2 = .077$) was moderate to large, indicating a practically relevant difference between girls and boys. For *auth*, the effect was moderate ($\eta^2 = .046$), indicating a clear but less pronounced difference. Both results emphasize that gender might be an additional significant factor for the constructs examined.

Discussion

The present study examined the role of perceived authenticity in the development of situational interest during a context-based out-of-school chemistry intervention among early adolescents (aged 14–16). While individual interest in chemistry was relatively low, interest in medicine was notably higher, aligning with the study’s intentional focus on medical contexts.

Correlation analyses revealed that perceived authenticity was strongly associated with all key constructs, particularly suggesting it being increasingly important for interest development over time. Mediation analyses confirmed that perceived authenticity partially mediated the effects of both *ind(ch)* and *ind(med)* on post-test situational interest. This supports the hypothesis that perceived authenticity acts as a key psychological mechanism for interest enhancement.

The ANOVA results underline that the perception of authenticity could play a central role in the development of situational interest during the intervention, as no significant difference between learners from the “interest gain”-group and “interest loss”-group could be found in the other constructs examined. Gender also appears to be related to the perception of authenticity, albeit with smaller effect sizes. It is noteworthy that, despite their significantly higher perception of authenticity compared to boys, girls do not show a generally higher level of situational interest. Here, the hypothesis could be put forward that different learners may require different levels of ”threshold authenticity” to experience an increase in their situational interest, especially if their dispositional starting position already favours an increased perception of authenticity. Partial

mediation was found for both mediation analyses, suggesting that an increased experience of authenticity, in parallel with the existing dispositional situations, promotes an increase in situational interest.

The increasing relevance of authenticity over time may reflect a growing sense of personal relevance and connection to the content. This claim is additionally supported by data from the written statements about the individual authenticity perception. Students from the "interest gain"-group who expressed high perceived authenticity often stated that they had the feeling that the patient file is an example of a phenomenon experienced by a lot of people in daily life. They also often noted that the experiments were only modelling medical procedures but helped them understand important steps towards the diagnosis.

Together, these results suggest that interventions aiming to enhance situational interest should not only focus on content relevance but also on fostering students' perception of authenticity. Future research should explore how authenticity can be intentionally cultivated in classroom settings, particularly through narrative-based, or real-world connected learning experiences.

Conclusion And Outlook

The results of the mediation analysis and group comparisons show that although the perception of authenticity plays a decisive role in the development of interest, the relationship appears to be much more complex than what can be described by a linear relationship or group classification. Accordingly, an increased experience of authenticity could promote an increase in situational interest even if the initial situation in terms of individual interests is not considered favourable per se. At this point, next steps would involve testing the correlations and mediations already identified with a larger sample size in a structural equation model to consider the weighing of the individual items for the distal variables and to be able to draw causal conclusions at the same time. An analysis of possible clusters or profiles also seems promising for identifying gradual developments, as smaller and larger changes in situational interest are currently being considered collectively.

For optimization of our learning environment, it seems highly promising to include steps of guidance for students struggling with drawing the connections between the learning content (the case file) and their own life experiences. To exploit the potential of perceived authenticity as a mediator in the development of situational interest, it seems advisable to keep the contexts linked strongly to authentic relevance in daily life to successfully to mitigate the non-profitable influence of low individual interest. A qualitative follow-up study could provide information on the exact conditions or triggers of the feeling of authenticity to make the findings usable across contexts and disciplines. If authenticity can be used adaptively for learners with different sets of individual dispositions in future learning environments, our approach of authentic contexts seems suitable to make chemistry appealing even for students with lower individual interest.

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ESERA 2025 Copenhagen

Using The Four-Quadrant Model To Examine The Character And Value Development Of Pre-Service Primary Teachers About Global Warming

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Due to the alarming consequences of environmental issues, moral dilemmas, and the rapid advancements in science and technology, researchers are now doubting the effectiveness of character and values education. In order to solve current issues and promote a just and peaceful global society, there is an increasing focus on educating people to have an ecological worldview, social and moral compassion, and socio-scientific accountability. Given the significance of the early years in the formation of character and values, the goal of this study was to assess and improve pre-service primary school teachers' character and values holistically using Wilber's four-quadrant model. The study was carried out utilizing a multiple case study methodology and featured two individuals. The pre-service teachers' responses to interview questions both before and after the implementation served as the data sources. Deductive content analysis showed that participants demonstrated enhancement by incorporating more character and value elements in their explanations or by offering more detailed elucidations on these characteristics across all quadrants after the implementation. Therefore, Wilber's four-quadrant model provides a new and effective perspective for assessing and developing the character and values that people of the twenty-first century are supposed to have.

Keywords: pre-service primary teachers, character and value, four quadrant model

Introduction

21st-century character and values include ecological worldview, social and moral compassion, and socio-scientific accountability (Choi et al., 2011). To train individuals who promote social virtue, other people's rights, and the common good (Singh, 2019); behave responsibly on global concerns; and make effective ethical judgments, these characters and values must be fostered.

The ecological worldview addresses interconnectedness and sustainability, as well as being conscious of ecological issues (Lee et al., 2013). Empathy, respect for life, and compassion for the environment and individuals impacted by environmental issues are social and moral compassion. It involves moral and ethical sensitivity, empathy, and perspective-taking (Choi et al., 2011). Socioscientific accountability requires recognition of stakeholder duties (responsibility), the science and society relationship, and action (willing to act) (Choi et al., 2011).

Science education may incorporate character and values through group discussions, argumentation, inquiry, and field excursions (Lee et al., 2012). Many believe character and value development should encompass cognitive, emotional, and behavioural elements in a more holistic way (Khobir & Hasanah, 2021). Comprehensive character education helps students identify their identities and aspirations via social, moral, and environmental links (Khobir & Hasanah, 2021). Wilber's (2000) four-quadrant method develops personalities individually, collectively, internally, and externally in terms of "I (thoughts, emotions, memories)," "We (material body, visible behaviour)," "It (shared value and meanings)," and "Its (systems and government)" perspectives.

This study used Wilber's (2000) model to develop and assess pre-service teachers' character and values by focusing on global warming. Global warming might have dire consequences for the environment, economy, and society (Guterres, 2024). Ecological education, moral and social awareness, and socio-scientific responsibility can prevent global warming. This study intends to develop the character and values of pre-service primary teachers in each quadrant in light of global warming. The guiding question is:

How does the four-quadrant model of global warming help pre-service primary school teachers to develop an ecological worldview, socioscientific accountability, and social and moral compassion?

Method

We employed qualitative multiple case studies with two female pre-service primary teachers studying at a state university in Türkiye. TEAMS and Classroom were used for the lessons in ten weeks after two severe earthquakes hit Türkiye in 2023. Through implementation, the four-quadrant model structured global warming teaching, including activities that support character and values. For instance, sharing information about countries most and least affected by and contributing to climate change was carried out to foster empathy, calculating and discussing individual carbon footprints was realized to foster responsibility, and discussing the consequences of global warming was realized to foster an ecological worldview.

Data Collection And Analysis

The current study adapted Nolan's (2021) perspective-taking questions to collect data. Questions were adapted in four quadrants to represent character and values. Students uploaded their answers in the classroom before and after implementation. The gathered data underwent deductive content analysis. The replies of the participants (Fatma and Leyla) were assessed on the character and value components in each quadrant.

Findings

The findings are presented within the context of each quadrant under the headings of ecological worldview, social and moral compassion, and socio-scientific accountability.

Ecological Worldview

Q1: Fatma presented her ideas in terms of sustainability before implementation. She made explanations regarding sustainability and interconnectedness after implementation.

Initially, Leyla expressed her opinions without considering sustainability or interconnectedness. After implementation, she addressed them.

Q2: Fatma first did not evaluate her behaviours in terms of sustainability and interconnectedness. After implementation, she highlighted that her actions may affect future generations and underprivileged nations (sustainability and interconnectedness).

Leyla originally ignored her behaviour's impact on sustainability and interconnectedness. After the implementation, she said she minimizes her carbon impact for future generations (sustainability).

Q3: Fatma initially lacked sustainability and connectedness explanations for people's shared beliefs. She stated her society recognized global warming and its effects after implementation (interconnectedness).

Leyla never highlighted people's sustainability and connectedness values before or after implementation.

Q4. Fatma said industrialized nations' policies adversely affect non-global warming countries. (interconnectedness). She discussed nations' policies in terms of ecological balance following the implementation (interconnectedness).

Leyla initially explained population growth causes global warming (interconnectedness). Following the implementation, she named various global warming factors and held wealthy nations liable (interconnectedness).

Social And Moral Compassion

Q1. Initially, Fatma expressed her deep concern and sadness about the effects of global warming (emphatic concern). Following implementation, she emphasized that human actions that cause global warming are immoral and unethical, demonstrating her sensitivity to moral and ethical issues.

Initially, Leyla demonstrated empathy for global warming's detrimental repercussions. After the implementation, she made explanations regarding emphatic concern, moral and ethical sensitivity, and perspective taking.

Q2. Fatma explained moral and ethical sensitivity because of her behaviours both initially and after the implementation.

Initially, Leyla did not evaluate her behaviours in terms of social and moral compassion; after implementation, she made explanations regarding moral and ethical sensitivity and emphatic concern by referring to her behaviours.

Q3. Initially, Fatma showed moral and ethical sensitivity because of people's behaviour around her. After implementation, in addition to moral and ethical sensitivity, she stated that people feel sad because of the effects of global warming (emphatic concerns).

Leyla noticed that people don't examine how their activities affect global warming (perspective-taking) and feel awful for those impacted (emphatic concern). After implementation, she only made explanations regarding perspective taking for her society's values.

Q4. Fatma stated that countries do not tackle global warming with moral and ethical sensitivity. After the implementation, she said developed nations felt morally responsible because of their activities contributing to global warming (moral and ethical awareness).

Leyla also said that countries do not act with moral and ethical sensitivity but later stated that they feel ethical and moral sensitivity.

Socioscientific Accountability

Q1. Fatma initially stated her responsibility to care for living things affected by global warming. After implementation, in addition to responsibility, she stated her desire to be willing to act.

In addition to the responsibility stated initially, Leyla expressed a willingness to participate in efforts (willingness to act) after implementation.

Q2. Fatma stated that she wants to join activities that would help her become more conscious of global warming before and after implementation.

In addition to the willingness to act stated initially, Leyla explained her contribution to global warming (responsibility) and desire to change her habits (willingness to act).

Q3. Fatma stated that the people around her are aware of global warming and are willing to act in preventive actions. After implementation, she remarked many around her want to act but don't.

Initially, Leyla stated people around her don't feel responsibility for global warming. After implementation, none of these people has a desire to act, she said.

Q4. Initially, Fatma didn't know what other nations were doing to address global warming. She added, following the implementation, that other countries are taking responsibilities and creating environmental protection measures (willing to act).

Leyla had no idea how other nations viewed global warming. After implementation, she noticed that other countries are planning for climate change (willing to act) and feel responsible.

Discussion

Following implementation, participants discussed their ecological worldview and opinions on global warming, indicating a development. This increase was sometimes observed by addressing more environmental worldview sub-elements and sometimes by providing more explanations for these elements. Information-oriented and reflective activities may have supported the development of participants' ecological worldviews. Participants can develop awareness of their mental state and reflect on their ideas, responses, and emotions surrounding global warming by focusing on the inner world (Esbjörn-Hargens, 2006; Tønnesvang et al., 2015). In addition, the fact that scientific explanations offered are advanced by the information acquired on a subject (Hakyolu & Ogan-Bekiroğlu, 2016) supports this finding.

Other findings of the study are about social and moral compassion. The study reveals that teaching complex scientific issues like global warming enhances students' empathetic concern and moral and ethical sensitivity in accordance with Fowler et al. (2009). Especially, pre-service teachers could discuss additional aspects of social and moral compassion of their behaviours and other countries, possibly due to their moral and ethical assessments of self-behaviours and gathering new information during the study. However, participants' ability to take perspective was lacking. This could be as a result of the present study's increased focus on studying global warming and its reduced number of decision-making-related tasks.

Other findings of the study are about socioscientific accountability. Fatma focused on educating individuals to increase awareness about global warming, while Leyla declared her readiness to take personal action. This suggests that people's approaches to global warming are influenced by their values and character elements. Studies indicate that personal perspectives significantly influence teachers' selection and presentation of information on global warming (Sadler, 2004). Both Fatma and Leyla expressed that society is prepared to combat global warming, but they gave different justifications for this. This may be because people at different educational and socio-economic levels may not be consciously concerned about environmental issues or engage in environmentally friendly behaviours when little is known about the problem or its solutions (Gifford & Nilsson, 2014). They also discussed how nations approach the problem in terms of being willing to act and feeling responsible after implementation. Gaining information about policies and agreements in other countries could have allowed for inferences about countries' socioscientific accountability.

Conclusion And Implications

Participants showed improvement by including more character and value elements in their explanations or by providing more explanations about these elements in all quadrants after the implementation. Therefore, this study's findings offer a new and holistic perspective on developing and assessing character and value elements using a four-quadrant model. Future research might examine the effects of teaching various subjects. Both quantitative and qualitative data may also support these conclusions, and various decision-making exercises may encourage participants to adopt new perspectives.

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ESERA 2025 Copenhagen

Technology Blindness: The Loss Of Affinity And Awareness For Technology

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*In recent years, the number of first-year students in STEM subjects, particularly in engineering and technical degree programs, has been declining in Germany. This development is worrying in view of the growing shortage of skilled workers, as falling student numbers can impair Germany's innovative strength and competitiveness in the long term. This paper proposes that this trend can be attributed to a general loss in the perception of technology. This loss is referred to as "technology blindness", an adaptation of the existing term "plant blindness" from biology. One approach to counteracting this is Inspir**ING**®, an elective course at Karlsruhe University of Applied Sciences in which students prepare and carry out a teaching unit for pupils based on an experiment. The didactic methods such as storytelling, didactic reduction and experiments form the foundation of these units. Participants in the conference workshop experienced such a teaching unit live as an example. This workshop aimed to introduce the concept of "technology blindness" and demonstrate to participants how the Inspir**ING**® methodology can reduce it and sharpen awareness of technology.*

Keywords: STEM, engineering, technology blindness, awareness, interest

Note

In order to distinguish between secondary school students and students of engineering subjects at the university, secondary school students are referred to as *pupils* and students at the university as *students*.

Introduction

As one of the world's leading industrial nations, Germany is facing a critical challenge: the number of first-year students studying STEM subjects (science, technology, engineering and mathematics) is falling, particularly in engineering disciplines (Anger et al. 2024). This is an alarming development as it correlates directly with the growing shortage of skilled workers. According to reports, there is already a shortfall of around 140.000 STEM professionals (Plünnecke, 2023). This could permanently weaken Germany's innovative strength and international competitiveness. In the long term, this trend could undermine the country's ability to respond to technological upheaval and maintain its position at the forefront of research and development (Shambaugh et al. 2017; BDI et al. 2024).

This paper proposes that one cause of this problem is a social phenomenon introduced as "technology blindness". Similar to the term "plant blindness" in biology (Wandersee and Schussler, 1999), "technology blindness" describes the growing lack of awareness of and appreciation for the constantly present technology in our modern world. Due to the apparent limitless availability of technology, awareness of its complexity, history, and fundamental contribution to our daily lives and solving global problems is dwindling.

To help address this issue, Karlsruhe University of Applied Sciences developed the elective Inspir**ING**® in 2019. The program takes an innovative didactic approach: engineering students become role models for pupils in eighth grade and above. The students design and lead 45-minute, experiment-based teaching units.

This paper first sets out the theoretical foundation of the concept of technology blindness. Then, the Inspir**ING**® program's didactic trio of storytelling, didactic reduction, and experimentation is explained in detail. Next, the practical implementation of this methodology is demonstrated using the workshop held during the ESERA conference in Copenhagen 2025. Lastly, this approach's implications for STEM education are discussed, and a future research outlook is provided.

Theoretical Framework: Definition Of "Technology Blindness"

The concept of "technology blindness" is a direct adaptation of the term "plant blindness," which was coined by biologists Wandersee and Schussler in 1999. These scientists used the term to describe the human tendency to ignore the plants in our environment, underestimate their importance to the biosphere, and regard them as passive, static backdrops. It is argued that an analogous phenomenon exists in the context of technology. To draw attention to this problem, a clear and precise formulation is necessary.

"Technology blindness" refers to the inability to consciously perceive technology in one's living environment, recognize its importance to society, and appreciate the complexity and ingenuity of technical objects. To define the term precisely, the characteristics that Wandersee and Schussler formulated for "plant blindness" are transferred to the technical context.

The specific characteristics of "plant blindness" are listed in Table 1 in the left-hand column; the transfer to "technology blindness" is listed in the middle column. The third column lists concise examples of technology blindness characteristics. These examples were used in the workshop held during the ESERA conference in Copenhagen 2025.

Table 1. Adapted features and examples.

plant blindness (Wandersee, Schussler, 1999, p. 82)	*technology blindness*	*Everyday example*
"The inability to see or notice the plants in one's environment	The inability to see or perceive technology in one's own environment	"I never consciously realized that even a simple light switch is technology."
the inability to recognize the importance of plants in the biosphere and in human affairs	the inability to perceive technology as an opportunity to solve environmental and human problems	"I have seen solar panels but never realized that they actively contribute to solving environmental problems."
the inability to appreciate the aesthetic and unique biological features of the life forms that belong to the Plant Kingdom	the inability to perceive, understand and appreciate unique features of technical objects in a wider technological context	"I often used GPS without understanding how complex the technology behind it actually is."
the misguided anthropocentric ranking of plants as inferior to animals and thus, as unworthy of consideration"	the perception of technology as self-evident and limitless availability, thus neglecting its true value and impact.	"I only realized how much I take technology for granted in everyday life when my Wi-Fi went down."

These four characteristics of "technology blindness" manifest as a passive consumer attitude toward technology. The smartphone becomes a "black box", electricity just comes out of the socket, and complex infrastructure systems remain invisible as long as they function properly. This lack of awareness results in a diminished basic understanding of technical principles, which ultimately leads to less interest in actively shaping the technological future. This directly impacts the choice of study and career fields.

Elective Program InspirING®

The elective program Inspir**ING**® at Karlsruhe University of Applied Sciences is a possible approach to counteracting technology blindness. Launched in 2019, the program creates practice-

oriented educational units that aim to raise awareness of technology among pupils, as well as stimulate their fascination with it.

A central aspect of the Inspir**ING**® program is its use of peer tutoring, as essential didactic element. Engineering students develop and teach a 45-minute lesson to pupils in the eighth grade and above. This format appeals to two target groups simultaneously, generating double the added value.

First, the program provides pupils with low-threshold access to technical topics by introducing them to young, authentic role models. The small age gap and comparable social status of learners and tutors promote interaction on an equal footing and reduces the hierarchical barriers that exist in traditional teaching and learning situations. In this way, technical content becomes accessible not only cognitively, but also emotionally. Second, students also benefit in several ways from their role as peer tutors. Reducing complex technical content to key principles and communicating it appropriately promotes didactic and communication skills. At the same time, this process deepens their understanding of the subject. Additionally, students reflect on their personal motivations for studying and actively take on the role of ambassadors for their field of study. (Struck, 2023)

The Inspir**ING**® program's overarching goal is to counteract technological blindness by providing positive, self-effective learning experiences that spark long-term interest in STEM education and careers.

Didactic Methodology

The efficacy of Inspir**ING**® is predicated on the synergistic interaction of the three didactic elements storytelling, didactic reduction, and an experiment (see Figure 1). These methods are closely intertwined, mutually dependent and form an inspiring and sustainable learning experience. The individual methods are described in more detail below.

Storytelling

Storytelling is known to establish an emotional and narrative framework. This can give teaching units a vibrant and exciting structure that appeals to pupils emotionally, arouses their curiosity and thus mesmerizes them. (Heering, 2016; Hadzigeorgiou et al. 2011) The program uses this to effectively capture the viewer's attention and to successfully embed the seemingly arid scientific subjects in meaningful contexts. The intention is to spark a greater interest in technology among pupils, not least as an incentive for a future career in science and engineering (Blum & Heering, 2014). Within the framework of Inspir**ING**®, storytelling is employed on two distinct levels:

1. Narrative framing: The scientific topic is embedded in a narrative that is designed to spark curiosity and interest among pupils. Rather than initiating the lesson with formulaic explanations, students begin the lessons with a challenge, an analogy, or a captivating observation, to name a few possible options.

2. Personal stories (peer learning): Students share their own enthusiasm and career paths. The incorporation of personal narratives into the educational experience serves to render abstract concepts and professional disciplines more accessible and relatable to pupils. These authentic narratives about motivation, challenges, and fascination act as a powerful incentive, break down barriers and establish an emotional connection with the pupils.

Didactic Reduction

Didactic reduction functions as a link, ensuring the experiment´s complexity and the underlying theory becomes understandable, manageable, and applicable to the target group. Complex technical and scientific topics are often inaccessible to pupils. The concept of didactic reduction

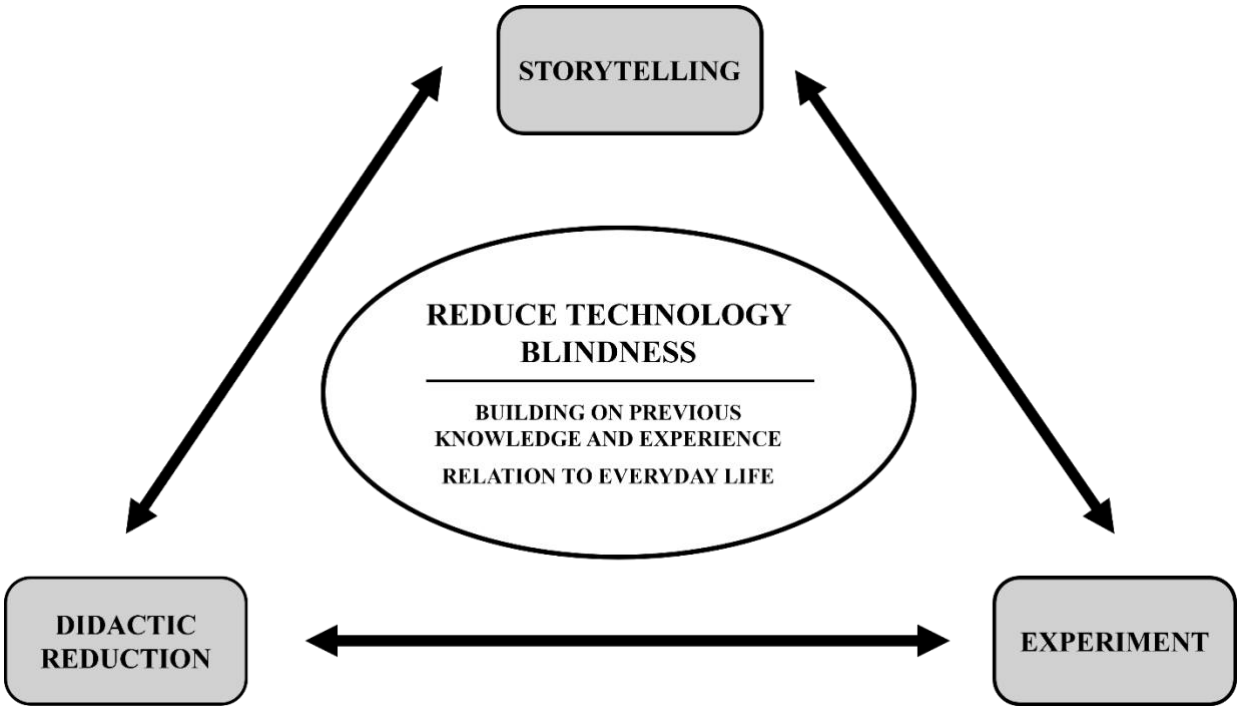
can be defined as the art of simplifying complex subjects without compromising technical accuracy. According to Lehner (2024), this process entails the selection of essential content, an emphasis on the core principle, and the simplification of the presentation. For students, this necessitates the process of distilling the theoretical framework of their experiment to a comprehensible level, suitable for pupils in grade 8 and above, without requiring any prior knowledge. This process also benefits students, as it requires a deep understanding of the topic in order to reduce it to its essential elements.

Experiment

Knowledge and insights are best gained by linking theory and empiricism helping students to understand technical phenomena better (Pusch et al. 2024; Pfangert-Becker, 2010). Thus, the experiment is the central element of the lesson. Active participation and self-directed discovery have been shown to result in a deeper and more lasting understanding than traditional frontal teaching methods. By establishing the experiment, conducting the tests, and ultimately completing the project independently, pupils can achieve a sense of self-efficacy and enthusiasm, often accompanied by a moment of profound realization. This shift enables them to transition from a passive stance as listeners to an active role as creators.

The common goal of these three approaches is to reduce technology blindness and raise pupils' awareness of technology. Also linking the content to familiar contexts, such as specific references to everyday life, and taking into account the target group's level of experience in order to build on existing knowledge are essential for a successful integration in long term memory (Hadzigeorgiou et al. 2011).

Figure 1. Interdependence of methods with the aim of reducing "technology blindness", own illustration.



Workshop At The ESERA Conference

A workshop called "Technology blindness – The loss of affinity with technology and how to counteract it" was held at the ESERA conference in Copenhagen 2025. The workshop demonstrated the practical application of Inspir**ING**® using an experiment with electromagnetism as an example to explain the idea of technology blindness and to sensitize participants to this

particular technology. The subsequent section delineates the workshop's structure and methodology in detail, as it was implemented as a constituent element of the conference program.

Background

> Any sufficiently advanced technology is indistinguishable from magic. (Clarke, 1973, p. 21)

The phenomena of electromagnetism largely elude our senses. Apart from the small fraction visible to the human eye, it is imperceptible to us. Yet the effects caused by electromagnetism are omnipresent. They range from experiences in our daily lives to enable technologies such as wireless communication, electric drives and navigation systems.

The fact that the cause of these effects is not observable, but quasi “invisible”, can give reason for a certain fascination. What at first sounds a little magic has been commonplace in the natural sciences for centuries: observing things and processes that remain hidden from the eye (Kube, 2019).

This is where the workshop comes in, using a storytelling approach to convey the topic. For example, magnetism becomes visible in everyday life when magnets attach notes or pictures to some metallic surfaces. A compass that is aligned with the earth's magnetic field makes the natural magnetic field directly tangible. By comparing it to magic and the analogy to invisible forces that work like magic, an emotional connection is created, curiosity is aroused and access to the topic is made easier (Heering, 2016; Hadzigeorgiou et al. 2011).

To demonstrate this, magnets are provided at the beginning of the workshop so that participants can experience the phenomenon of magnetism by themselves.

During the workshop, participants are engaged with the didactic methodology of Inspir**ING**®.The invisible force of magnetism is presented as a form of "modern magic" that can be understood through science. The personal narrative of a former Inspir**ING**® student and employee, from his dream of becoming an inventor to studying engineering and technology entrepreneurship, makes the engineering profession tangible and human. This use of storytelling aims to make people curious and excited to learn.

The following section describes the setup and underlying principle of the workshop experiment. The point of the experiment was to keep a permanent magnet suspended in mid-air using an electromagnet (see Figure 2). This requires an active control system to maintain the unstable balance between magnetic attraction and gravity. The setup has four main parts:

1. Permanent magnet: The object that is made to levitate.

2. Electromagnet: A coil that is used to create a magnetic field. The strength of the magnetic field depends on the electric current flowing through the coil.

3. Magnetic sensor (Hall sensor): It measures the strength of the magnetic field and thus indirectly the distance between the permanent magnet and the electromagnet.

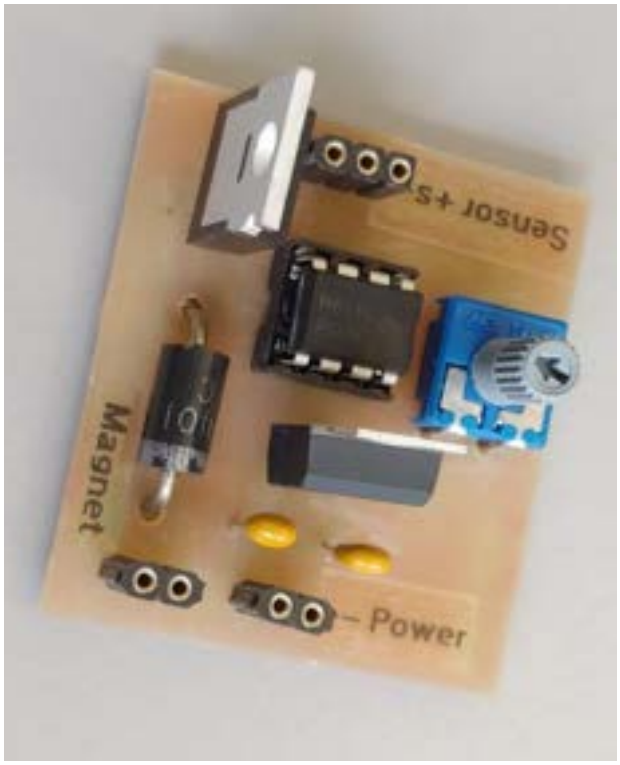
4. Control circuit (see Figure 3): An electronic circuit that processes the signal from the sensor and switches the electromagnet on when the distance becomes too great (the magnet threatens to fall) and off when the distance becomes too small (the magnet threatens to jump onto the electromagnet).

The task of the participants was to calibrate the switching threshold on a potentiometer on the circuit board so that the magnet is held in a stable levitation.

Figure 2. Floating ball magnet, own photography.



Figure 3. Control circuit, own photography.



Schedule And Implementation

The workshop followed a clear structure that integrates didactic principles:

1. Awareness check (beginning): At the beginning, participants are asked to rate their own perception of electromagnetism in everyday life on a scale (see Figure 4). This serves as a baseline measurement and makes the phenomenon of technology blindness directly tangible.

2. Introduction and story: The moderators introduce themselves (personal story), introduce the topic using the "magic" narrative and briefly explain the fundamental principles of the experiment.

3. Experiment phase: Participants receive boxes with components and instructions. They set up the experiment, connect the components, and begin the crucial calibration process. This phase requires patience and dexterity and promotes problem-solving skills.

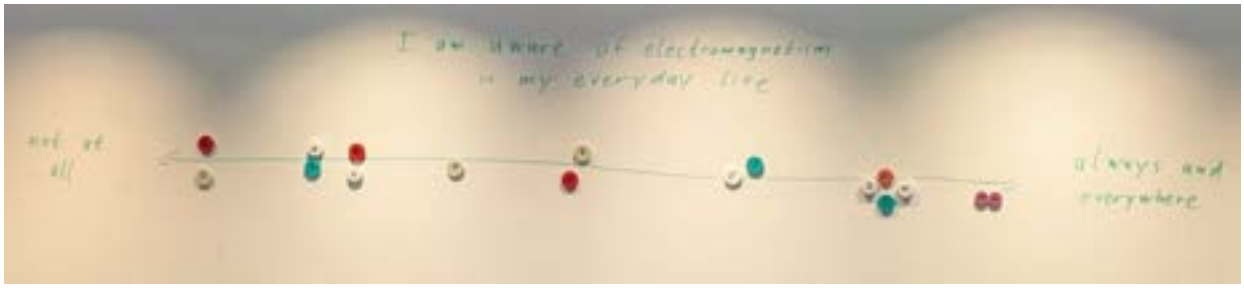
4. Levitation (moment of success): The success of the experiment (the floating magnet) is the highlight and creates a strong sense of self-efficacy.

5. Transfer to everyday life: Working in pairs or groups, participants collect examples of how electromagnets are used in everyday life. Examples such as electric motors, loudspeakers, scrapyard magnets, and magnetic levitation trains are then presented to illustrate the relevance of the principle learned.

6. Awareness check (end): Participants reevaluate their perception of electromagnetism. The

expected increase in awareness serves as evidence of the success of the intervention and as a basis for discussion.

Figure 4. Awareness scale, own photography.



Outlook

The workshop described, which incorporates the Inspir**ING**® program, offers valuable ideas for STEM education and shows a possible way to increase interest in STEM subjects.

It also showed that it is possible to raise awareness of complex technical phenomena in a short period of time. The before-and-after comparison of self-assessment in the workshop serves as a simple but effective indicator of a shift in perception away from technological blindness and toward a more sensitive perception. The program thus addresses a previously little-noticed but plausible cause of the current shortage of young talent in the engineering sciences.

The pedagogical triad of storytelling, reduction, and experimentation proffers a substantial and adaptable template for the design of inspiring STEM learning units. The paradigm shift from pure knowledge transfer to the creation of meaningful and motivating experiences is evident in the impressive demonstration of the floating magnet, which transforms abstract physical principles into tangible and fascinating learning experiences.

A more thorough examination of the long-term effectiveness of such brief interventions on study and career choices is necessary, and this can be best accomplished through longitudinal studies. However, the preliminary outcomes in terms of interest and perception indicate that initiatives such as Inspir**ING**® can serve as a pivotal foundation for cultivating the next generation of engineers, researchers, and technically proficient citizens. It is therefore imperative to deliberately address technological blindness to ensure the future of STEM talent and fortify Germany as a hub for innovation.

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Species Portraits As A Means Of Crossing Boundaries To Other Life Forms

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The aim of this study is to identify aspects of nature connectedness in the personal experiences of participants while engaging with the natural world. In this contribution we will introduce the concept of aesthetic species portraits as a method for facilitating an experienced personal connection between human and non-human life forms in their natural environment. We report qualitative fieldwork in the form of interviews, video recordings, photographs and creative work from a summer school held at a rewilding project area in Denmark. During a four-day intervention pre-service science teachers and science educators participated in co-creation of art-based artifacts using aesthetic methods of representation of species encountered in the area. We employed four young passionate experts to introduce the pre-service science teachers to the high diversity environment focusing on its natural inhabitants. This introduction created an immersive engagement with place. During the next days we chose subjects among the encountered species and created portraits. We identified the key themes in our data using an abductive thematic analysis with intercoder reliability checks. We discuss empirical findings from our intervention in the light of the concept of nature connectedness. We found that the process of co-creation, the immersive nature of the intervention and the personal encounters with species had transformative effects on the participant's perception of nature.

Keywords: Affective dimensions, Field experience, Pre-service teacher education

Introduction

> Doing science with awe and humility is a powerful act of reciprocity with the more than human world. I've never met an ecologist who came to the field for the love of data or for the wonder of a p-value. These are just ways we have of crossing the species boundary, of slipping off our human skin and wearing fins or feathers or foliage, trying to know others as fully as we can. (*Kimmerer 2020, p. 252*)

Science education focuses increasingly on aesthetic learning processes, particularly in relation to education for sustainable development (Heras et al. 2017). The concept of nature connectedness has been proposed by psychological research as a prerequisite of environmental engagement. In these contexts, aesthetics often enters the science teaching discourse as part of STEAM pedagogy, introducing aesthetics as concept from the humanities aimed at increasing participation and engagement (Peppler and Wohlwend 2018).

Nature connectedness is regarded as an emotional driver and has been suggested to be independent of the cognitive dimensions of science (Lumber et al. 2017). However, both aesthetics and the concept of nature connectedness have deep historical roots within the field of biology.

The natural historians who inspired Darwin and seeded the development of modern biology as a scientific field had a deep aesthetic involvement in their fields of research: In 1805, Alexander von Humboldt published his groundbreaking work on the relation between climate, elevation and botany under the title "Naturgemälde" – painting of nature – and in 1899 Ernst Häckel

meticulously described numerous species new to science in his book “Kunstformen der Natur” – artforms of nature.

The concept of nature connectedness can be traced back to the ecologist E. O. Wilson’s book “Biophilia” from 1984, in which he argues that biology, as a field of science, offers an approach to understanding the living world that aligns with our innate tendency to affiliate with other organisms. Wilson invites the naturalist approach, field biology, as a formula to reengage with the natural world: “To the extent that each person can feel like a naturalist, the old excitement of the untrammelled world will be regained” (Wilson 1984, p. 147). The perspective offered by biology allows observation of other life forms as subjects formed by the same natural processes as the observer themselves: A subject-to-subject encounter, so to speak, since humans are, biologically, one species among many, with our capacities of logic and reflection being one adaptive outcome among all the adaptations outlining the various species of our biosphere.

We explore species portraits as a way of engaging with other life forms, in which aesthetic representation of a species is interwoven with the aim of understanding the life forms we encountered. The aim was to identify aspects of nature connectedness in the personal experiences of participants while engaging with the natural world.

RQ: How do the facilitated species encounters help direct the focus of participants towards knowing a species as a non-human subject?

We will explore this research question through empirical data from a summer school held in the summer of 2024 at an unmanaged natural area in Denmark.

Method

We obtained our data from a four-day intervention during a summer school with the title: “Species, experiences and aesthetics”. The course enlisted 12 pre-service biology teachers, two early career in-service biology teachers, and three teacher educators (with a disciplinary background in biology) participating in designing species portrait activities. We took inspiration for co-creation and co-design from Sanders and Stappers (2008).

We collected qualitative data in the form of interviews, photographs, video recordings and creative artifacts produced during the summer school. At the end of the second and third day of the course, we presented portraits at a “vernissage” event where participants introduced their exhibited portrait, described meeting their species, how they chose their creative media, and the process of constructing the portrait.

In this contribution we report an analysis of a 55-minute video sequence recorded while co-creating a definition outlining the concept ’species portrait’ (video 1), as well as two group interviews with participants at the end of the course, lasting 23 minutes (interview 1) and 40 minutes (interview 2). Interviews were semi-structured, following a simple interview guide based on the course title: Respondents were invited to reflect on species they had encountered and portrayed, experiences they had encountered and their view on the aesthetic processes they had engaged in.

While co-creating the concept definition, one of the authors of this contribution wrote keywords from the dialogue on a flip-over, creating an open coding of points emerging from the conversation. A picture of the flip-over is shown in figure 1. From these codes the authors employed a thematic analysis and developed a coding scheme (Braun and Clarke 2006). Using these themes and codes from the flip-over to code, sequentially, video 1, interview 1 and interview 2, we broke down and reassembled our code structure through an abductive analysis

(Brinkmann 2014), which allowed us to recognize and include patterns emerging throughout the coding process.

Figure 1. A photo of the outcome of co-creating a definition of "species portraits" with course participants. English translations of the concepts emerging from the dialogue are superimposed on the photo.



Findings

Throughout the dialogue in the videos, the motif of sensory experiences emerged as a recurrent and dominant theme when describing species encounters: Respondents reported having engaged their senses in new ways, and they referred to the sensory experience of their particular species. Reports of the encountered species were highly affective, using a vocabulary of deeply personal connections, in several cases in relation to species encountered for the first time.

When asked about their experiences during the course, time and immersion became recurrent elements: Respondents reported a wide range of situations of solitude, absorption, increased awareness and meticulous studies of their chosen species. Many of the experiences reported were intimately related to place, indicating immersive engagement.

Discussion And Conclusion

We were able to mediate species encounters in a particularly rich natural environment, facilitated by young enthusiastic species specialists, and our participants were able to let these initial impressions grow and mature through a generous, curriculum free and immersive aesthetic engagement with their surroundings. But while this intervention does not reflect a common school reality, it did allow us to explore the potential offered by what Wilson called “the naturalist approach” (Wilson 1984). Our participants did not arrive with a deep knowledge of field biology,

but the saturated experience of an inhabited environment, and their aesthetic engagement with particular species initiated transformative processes.

Table 1. This table outlines main themes emerging through our abductive analysis of the interviews, exemplified through selected participant quotes.

	Selected quotes
Sensory engagement	Vanessa:*"Well, I thought it was a bit crazy, that the bees had actual scents […] they smelled like onions or… lemon. And then how you were able to get up that close. I think it was crazy, getting that close to a tiny little animal, such a tiny little bee"*
Time, place, immersion	Erica: *"Well, this is connected to the dung. So, well, the scarabs. I simply find them cute. I didn't know a thing about them. It's not that I am that knowledgeable now, but this, to sit and paint them. I ended up – because I was sketching, I think I drew the same one five times or so. And then you become… it's a really good way to learn to identify the species"*
Affective species descriptions	Birk: "*I think it has resulted in a much more personal affection for specifically the species you went after. You have really been chasing them for a reason, and personally I really want to learn more about them, and I think it is super interesting to capture them in a creative, an aesthetic fashion, making it more, I don't know, personal. That is cool".*
Transformative experiences	Bjørn: *"O told me about sundew, so I thought […] I will go hunting for this one. And I couldn't find my way, and I got lost, and I was alone, and it was sort of magic to come down there and see how, well, like, the bog was there, the quaking bog was there and you had to go out there, and you could feel how it was, like, suspended, and it was embraced by the forest. And there were these tiny sundews, and I was all alone, and I nearly shed a tear, actually."*

Bjørn, a participant describing his own science teacher identity as "sort of a molecular biologist and physiologist by nature, so I never really delved into the species thing" ended up being so affected by an encounter with sundew, that he "nearly shed a tear", while Erica described going from "not knowing a thing" about scarabs to spending a whole day with repeated sketching of one scarab, and concluding that she "just found them cute" (full quotes in table 1).

In spite of their self-declared low initial level of knowledge about field biology or species, and the lack of any assessment of knowledge or specified requirements of biological facts in the aesthetic products, participants embedded many perspectives of biological knowledge in their portrayals of species, from morphological details through life cycles and habitat requirements to effects of the species on ecosystem dynamics. In the interviews, several participants expressed enthusiasm not just for the species itself, but also for the knowledge gained while working on the portrayal. The cognitive side of learning about the species emerged as interwoven with the affective connection, the aesthetics of the creative process and the awareness of the subject of the portrait as a life form in its own right. In the words of Birk: "I really want to learn more about them, and I think it is super interesting to capture them in a creative, an aesthetic fashion, making it more, I don't know, personal. That is cool" (full quote in table 1)

A professional field biologist could be considered to be engaging in, as our opening quote from Kimmerer (2020) reads, "crossing species boundaries" by finding significant patterns in scientific

data describing other species. This level of insight is not readily available in a school science setting, or even in the educational setting of a teacher training program. Our species portraits can be considered short-cuts for creating this transcendent experience of a personal bond to a non-human life form in its natural environment.

Aesthetics has an inherently transcendental aspect in that it communicates affect and emotion from one human to another. The natural sciences, on the other hand, allow us to attempt understanding non-human life forms as subjects in their own right, thus representing another type of transcendence. Bringing the two together adds depth to the concept of nature connectedness by qualifying emotional attachment with curiosity and a desire for knowledge: Science can help us understand who they are, and aesthetics can help us feel that understanding is important.

We see indications of this transformative process in our participants' perception of nature, as reflected through the interviews.

Acknowledgement

We would like to acknowledge the staff at the Molslaboratoriet field station for allowing us to situate our field course in a truly inspiring natural setting, and our colleague, Therese Malene Nielsen for bringing new perspectives on time into our discussions.

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Detect, Define And Visualize Epistemic Emotions For Science Education

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Learning science is not solely a cognitive endeavour. The affective dimension has increasingly become a focus of science education research. Within this domain, growing attention is being given to constructs such as epistemic emotions and to novel methodologies used to investigate them. This contribution focused on an NLP (Natural Language Processing) analysis aimed at detecting epistemic emotions in the context of the discovery of the Theory of Special Relativity. The study was conducted by analysing a special text based on historical interviews with Albert Einstein, carried out by Gestalt psychologist Max Wertheimer in 1916, and published in 1945. From this analysis, the following results emerged: an operational definition of the construct of epistemic emotions, developed through three markers that can be applied to analyse other texts or interviews; the creation of a list of epistemic emotions, designed to facilitate their consistent classification and detection in future researches; a dynamic mapping and visualization of the epistemic emotions involved in the cognitive processes associated with the key phases of the genesis of the Theory of Special Relativity, using James Russell's circumplex model of affect. These findings offer tools to bring out and visualize the emotional dimension of problem-solving and scientific research activities. These tools can be both diagnostic and teaching resources, aimed at unpacking affective dynamics in educational contexts.

Keywords: Epistemic Emotions, Physics Education Research, Interdisciplinarity

Introduction

Recent special issues and handbooks have highlighted and formalized the relationship between affect and cognition in science education (Jaber et al., 2023; Vea & Jaber, 2026). Major cognitive theories — such as conceptual change theory (Posner et al., 1982) — have progressively emphasized the multi-layer landscape that has been progressively built to unpack the multiple dimensions and types of knowledge involved in conceptual change. The current research on conceptual change offers a landscape, that is grounded in the foundational work on the nature of concepts and conceptual change, and articulates in further four layers: the role of representations (such as language, visual representations and simulations, equations, and gesture) in concept representation and learning; the interplay between the epistemological practices of explaining, modelling and arguing and conceptual change; the relationship between conceptual change, metacognition, and student's epistemologies; the relation between identity development and conceptual learning in disciplinary domains (Amin et al., 2023). The last two layers point out the need to enrich the research on conceptual change with affective and emotional dimensions (Pintrich, 1993).

In this context, one of the ways of developing the affective dimension is focused on the epistemic emotions, namely the emotions engaged in the cognitive dynamics of learning (Jaber et al., 2023). These studies on epistemic emotions are shedding light on novel theoretical and methodological challenges.

As for the theoretical issues, the emotional dimension challenges the pure rational assumptions that stay behind the earlier theories of conceptual change (Amin et al., 2023) based, more or less explicitly, on a strict separation between the apparatus of rationality and that of biological regulation (Damasio, 1994).

As for the methodological issues, the debate is still very open and lively, being the emotional dimension particularly subtle and implicit. The wide variety of methods and approaches currently employed to "capture" epistemic emotions has led Jaber and colleagues to refer to a "generative non-convergence" typical of an expanding field of research. In fact, the state of the art shows a great effort to search for new creative methodological approaches aimed to keep a high level of rigour (Jaber et al., 2023). Video-interviews are a typical explored method for multi-modal analyses aimed to investigate the degree of connection between the emotion and the identified cognitive event. For instance, Jaber and Hammer use video interviews to uncover "entangled" emotions that characterize a general attitude toward engaging in science among very young subjects (Jaber & Hammer, 2016), while Gupta and colleagues examine video interviews to capture moment-by-moment epistemic emotions, focusing on short timescale local coherences in high school students (Gupta et al., 2018). More generally, it is recognized that text and natural language are primary vehicles for emotions, emphasizing the need for methods capable of analysing such datasets.

This study has been carried out to explore a pilot methodological approach for detecting and visualizing epistemic emotions, drawing on machine learning techniques for text processing and analysis. The method was tested using a historical text that examines the emotional dimension in the development of a scientific theory. Our goal is to refine and adapt this approach for use in classroom settings as well.

This pilot study was guided by the general research questions of how Epistemic Emotions can be recognized and operationally defined, and how they can be represented and visualized, including which models may be used; these questions were explored through the specific case study described below.

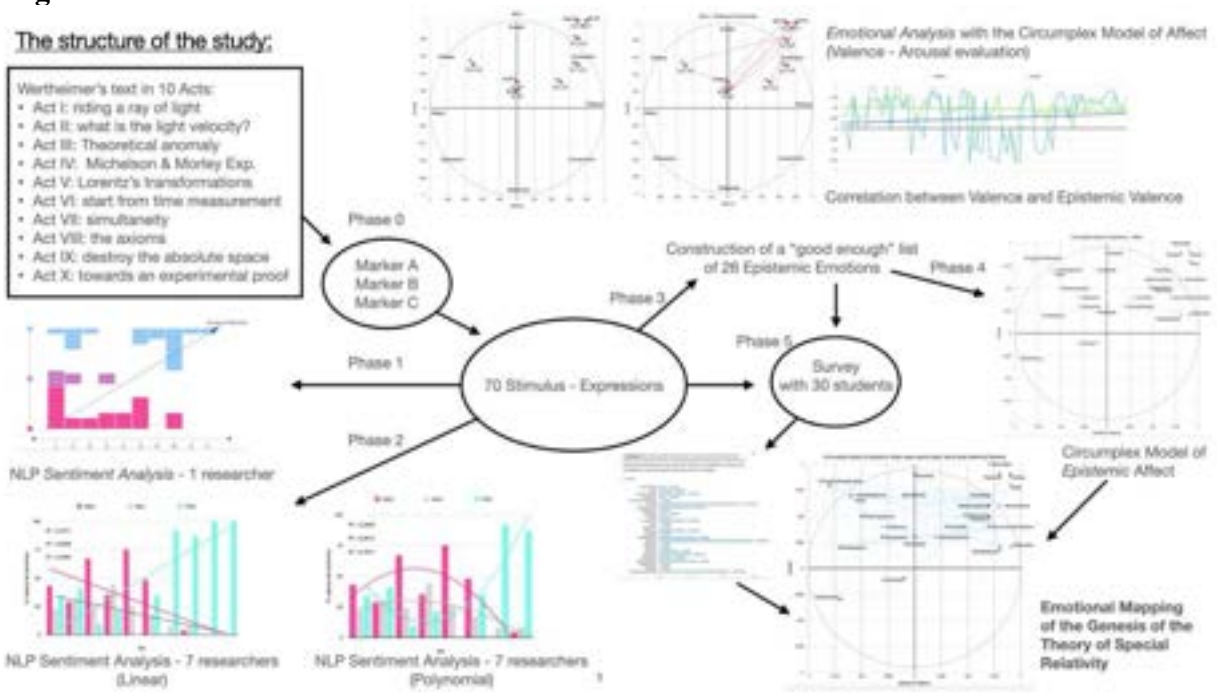
The Source Of Data On Epistemic Emotions

For the pilot study, the textual source of data we chose is the seventh chapter Einstein: The thought that led to the theory of relativity of the book Productive Thinking (Wertheimer, 1945, 2020; Miller, 1975). Max Wertheimer's text collects conversations with Albert Einstein on the genesis of Special Relativity. The conversations refer to a series of meetings that Max Wertheimer, exponent of Gestalt, had with Albert Einstein in Berlin since 1916. This chapter appeared as a suitable text for the analysis for three main reasons. The first reason is that the scientist also describes difficulties and emotional impulses in the genesis of a new scientific theory. The second reason concerns the text structure, organized into ten acts that delineate the pivotal phases of this specific research process. This format allowed the identification of moment-by-moment epistemic emotions (Gupta et al., 2018) and, owing to the open and conversational nature of the interview (Pussetti, 2010), also captured entangled emotional nuances (Jaber et al., 2023) that influenced the direction of inquiry (Jaber & Hammer, 2016). The third reason concerns the topic per se of the conversations: Special Relativity (SR). In fact, SR has been already widely investigated in its historical and philosophical dimensions (e.g. Pais, 1982) in the research on conceptual change (Posner et al, 1982; Hewson, 1982; Villani & Arruda, 1998; Levrini & diSessa, 2008; Levrini, 2013) and, more in general, in physics education (Sherr et al., 2001, 2002; Alstein et al., 2021; Miani, 2022). This constellation of studies, together with Einstein's metacognitive reflections, offers the possibility to triangulate the results obtained by a novel methodological approach to investigate epistemic emotions, that integrates psychological, conceptual, and epistemological dimensions.

Methods And Results

From a methodological point of view, the study was inspired by natural language processing (NLP) techniques (Das & Singh, 2023) to process Wertheimer's text. Through an initial exploration — individually conducted —, 70 specific linguistic expressions linked to emotions and associated with the phases of scientific research were detected. Examples of linguistic expressions highlighted are: "to trouble him", "intensely concerned", "Puzzling to think"... These expressions, termed stimulus-expressions, were identified to elicit and associate specific epistemic emotions. This preparatory phase also included the extraction of three markers — concise indicators designed to systematically detect stimulus-expressions within the text — essential for distinguishing, conceptualizing, and objectifying epistemic emotions linguistically. These markers through which epistemic emotions can be recognized and operationally defined are: A. emotional sound; B. epistemic sense and connection to a specific phase of the construction of the theory; C. liquid lexical structure (Figure 1 Phase 0).

Figure 1. Design and structure of the study. Phase 0: construction of the three markers for operationally defining epistemic emotions within the text. Phase 1 and 2: Visualization of Einstein's "feeling of direction" through an NLP-sentiment-analysis. Phase 3 and 4: Construction of the Circumplex Model of Epistemic Affect. Phase 5: emotional mapping of the genesis of SR.



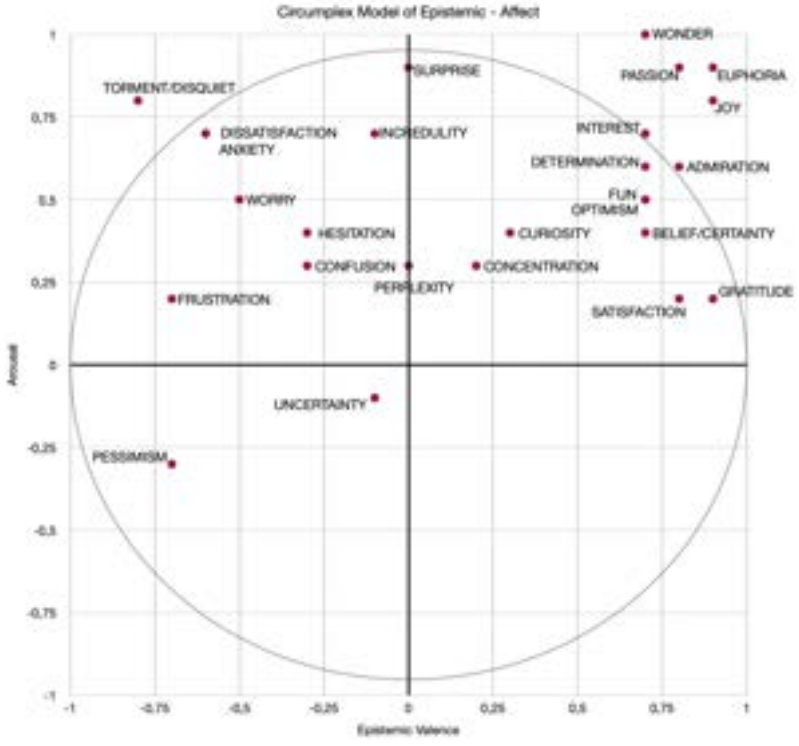
Thus a primary action was to extrapolate the visualization of Einstein's "feeling of direction" through an NLP-sentiment-analysis (positive-negative-neutral), which took place by processing 70 stimulus-linguistic-expressions extracted from the text, first of all individually and then — to make the result more robust — with the collaboration of 7 researchers in Physics Education, who evaluated again the stimulus-expressions through the three connotations (Figure 1 Phases 1 and 2).

It was found, using linear interpolation, that positive sentiment has an increasing trend while negative and neutral sentiment decreases as the theory develops. We also found the correlation between the positive sentiment and the solving phases of the research path. Using polynomial interpolation, it was surprisingly found that positive sentiment has a trend similar to that relating to the Denning-Kruger Effect (Dunning, 2011) as skills increase.

The preliminary results obtained in phases 0, 1, and 2 have corroborated the plausibility of the hypothesis that the text is rich in epistemic emotions and that these emotions can be detected. The following research phases led us to achieve the main findings.

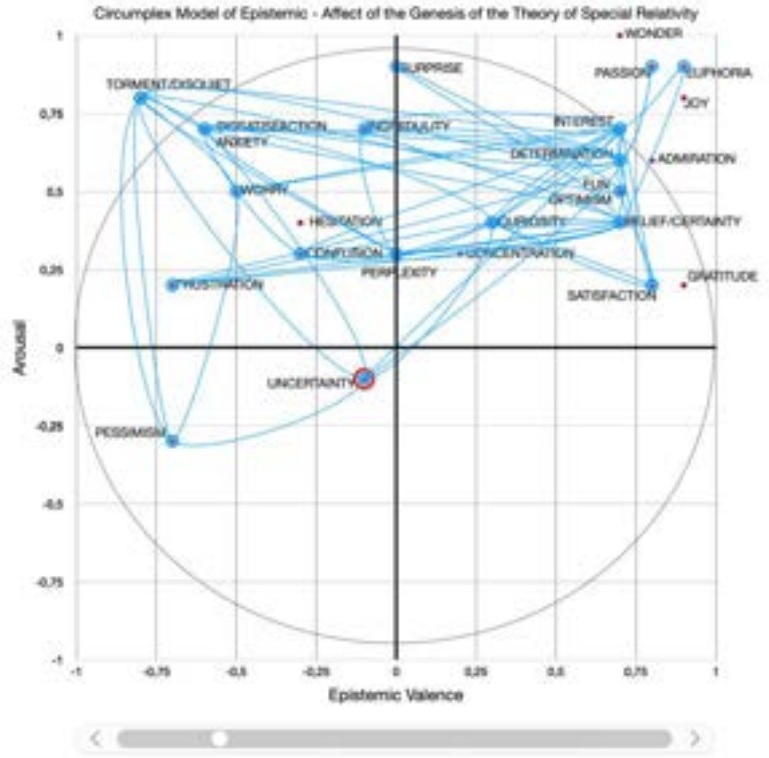
Going on in "dialoguing" with the text, considering the previous scientific literature on the topic of epistemic emotions and using a strong knowledge of Albert Einstein's work, a list of 26 epistemic emotions linked to problem-solving was created to refine the connotation of the 70 stimulus-expressions. This list is not supposed to be exhaustive, but it represents our first original finding: a novel plug-in that widens and extends the original functions of Russell's Circumplex Model of Affect (Russel, 1980). This model is used in disciplinary fields such as psychology and emotional robotics engineering and represents each emotion with a pair of coordinates — ranging from -1 to 1 — called Valence (from sadness to happiness) and Arousal (degree of activation, from sleepiness to excitement). Each epistemic emotion of the list has been positioned in the Circumplex Model of Affect (Figure 1 Phase 3 and 4; Figure 2), by assigning the values of Valence and Arousal. The assignment has been supported by AI as a stimulus and/or a check of the researchers' qualitative hypothesis. The process led us to turn the Circumplex Model of Affect into our second original finding: a draft of a Circumplex Model of Epistemic Affect (Figure 1 Phase 3 and 4; Figure 2).

Figure 2. Circumplex Model of Epistemic Affect.



Finally, through statistics on a sample of 30 students of a Physics Education university course, a correspondence was constructed between the 26 epistemic emotions in the list with the 70 stimulus-expressions in the text. Going into more detail, the survey took place by administering to the 30 students a format that highlighted each stimulus-expression and asked the subjects to associate every specific stimulus-expression with one or more epistemic emotions of the list. This allowed us to select the epistemic emotion that best characterized every specific stimulus-expression, and to insert all the 70 stimulus-expressions into the Circumplex Model of Epistemic Affect to arrive at the final emotional mapping of the genesis of the theory of SR, with a visualization and an animation on the circumplex showing its dynamics (Figure 1 Phase 5; Figure 3).

Figure 3. Emotional dynamics of the genesis of Special Relativity Theory built in the Circumplex Model of Epistemic Affect.



Conclusions

This research has corroborated the feasibility of constructing an increasingly specific definition of epistemic emotion through the analysis of a text with interviews with scientists. A novel methodology highlights the potential of an interdisciplinary research approach, which brings to light the affective dimension within scientific research processes. The Circumplex Model of Epistemic Affect (CMEA), born from the synergy between the circumplex model of affect and the development of a reference list of epistemic emotions, emerges as a novel tool designed to detect, define, and visualize epistemic emotions, offering a structured approach to assess the affective dimensions of scientific research and learning processes. Further studies will test and revise both the list and the Circumplex. We expect that the evaluation of Valence and Arousal of the single emotions can be made more and more robust. However, by leveraging the CMEA, researchers and educators can systematically identify and categorize these emotions, thereby making them more accessible and actionable within both research and classroom dynamics. The CMEA can operate as both a pedagogical and diagnostic tool and it could represent a significant step forward in integrating affective and cognitive dimensions into educational research and practices. From a pedagogical perspective, the visualization of Albert Einstein's scientific theorizing suggests that emotional trajectories in scientific inquiry are not linear or progressively cumulative, as often implicitly assumed, but rather characterized by fluctuations and reversals. Making such alternating emotional dynamics visible within a classroom pathopoietic process may be particularly illuminating for students, as it foregrounds the affective complexity inherent in authentic scientific problem solving. To check its diagnostic potential, the tool has been used to emotionally evaluate different phases of a classroom problem-solving process to elicit and make visible the affect dynamics associated with an experimental kinematics activity in a second-year upper secondary school class (Rimediotti, 2025). The results show the tool's effectiveness in unveiling students' emotional development throughout their learning processes.

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Part 3 / Strand 3

Science Teaching Processes And Instructional Design

Co-editors: *Italo Testa & Hanne Stammes*

Part 3 / Strand 3 Science Teaching Processes And Instructional Design

Theories, models, and empirical results about teaching processes, curriculum design and implementation. Includes design, adoption, exchange, refinement and transformation of teaching interventions, materials, and tools, including laboratory and inquiry-based practices. Also, research-based interventions and their role for curriculum design, instructional paths and learning goals, and classroom implementations, refinement, and evaluation of teaching-learning sequences; learning progressions, etc.; and models of codesign and factors that influence teachers ’roles, ownership, and accountability.

Sub-themes:

1) Design and Implementation of Inquiry-based and Laboratory Practices
2) Research-based Interventions in Curriculum Design and Instructional Paths
3) Evaluation and Refinement of Teaching-Learning Sequences and Learning Progressions
4) Co-design Models and Teacher Roles in Science Education

Contents

Strand 3: Science Teaching Processes And Instructional Design 136

What Factors Influence The Adoption Of Inquiry-Based Learning? A Comparative Study Between Chile, Spain, And Portugal 137

Several Reasons To Develop Symbols In Physics Education 142

A Structured Framework For Designing Syllabus-Focused Educational Escape Rooms (EERs) That Promote The Development Of Students' 4C Skills. 153

A Teaching-Learning Sequence For Heat Transfer And Nature Of Scientific Inquiry At Primary Education 160

"We Had A Lot Of Freedom." Learning Of Students With High Diversity In An Open Inquiry "Lernwerkstatt" Setting 170

Artificial Intelligence In Experimentation: A Bibliometric Approach 176

Strand 3: Science Teaching Processes And Instructional Design

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The contributions to the 2025 ESERA conference in this chapter present several research themes related to the focus of the strand. One dominant theme that emerges from the papers is the critical examination of Inquiry-Based Learning (IBL). This covers everything from the theoretical underpinnings of IBL and the systemic determinants of its adoption to its practical implementation in diverse classrooms. The contributions primarily focus on fostering student agency and scientific literacy by engaging learners in authentic scientific practices such as hypothesising, modelling and evidence-based argumentation. Another significant theme is the integration of cognitive and neuroscientific frameworks into pedagogical design. The five studies in this chapter utilise models such as the Five Pillars of the Mind (symbols, patterns, order, categories, and relationships) and the Model of Educational Reconstruction (MER) to align science instruction with the brain's natural learning processes. This cognitive focus also extends to developing specific 21st-century skills, often referred to as the *4Cs* (critical thinking, creativity, collaboration, and communication) framework, which are considered essential outcomes of modern science curricula. Other relevant trends that emerge from the synthesis of these works concern methodological innovation and teachers' professional development. In terms of methodology, the papers focus on gamifying and diversifying the learning environment. Examples include the use of educational escape rooms to promote collaboration and the implementation of learning workshops to support open inquiry in inclusive settings. With regard to professional development, the papers in this chapter emphasise that innovations such as inquiry-based Teaching-Learning Sequences (TLSs) require substantial support for teachers to be effective. Therefore, these contributions are at the forefront of science education research, as they bridge the gap between theoretical constructs and classroom reality. For example, by focusing on the nature of scientific enquiry and the role of domain-specific networks, such as symbols in physics, the studies move beyond simple content delivery towards fostering a deeper understanding of the epistemic practices of science. This aligns the contributions of Strand 3 with the global educational goal of producing scientifically literate citizens who are capable of dealing with the complexities of the present day.

Finally, in terms of their relationship with the conference themes, the contributions focus on digital advances in science education and sustainability. Specifically, the papers explore the digital transformation of education, particularly the development of digital tools designed to reduce barriers to inquiry and the integration of Artificial Intelligence (AI) into experiments and instructional design. Here, digital platforms are presented not just as tools, but as transformative agents that reshape cognitive processes such as metacognition and problem solving. Although less explicitly present, sustainability is integrated into the contributions through real-world scenarios designed to promote environmental awareness. Furthermore, open inquiry formats often utilise topics such as 'habitats and environments' to engage students with their local and global surroundings, thereby fostering the agency required to address future environmental challenges.

ESERA 2025 Copenhagen

What Factors Influence The Adoption Of Inquiry-Based Learning? A Comparative Study Between Chile, Spain, And Portugal

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Scientific inquiry is an effective strategy for improving students' scientific literacy. However, it is rarely used by teachers. This study aims to identify the variables that predict the use of scientific inquiry by Primary Education teachers in Chile, Spain, and Portugal. A multiple regression analysis of TIMSS 2019 data reveals that its enactment depends on several factors such as teacher training, school climate, and job satisfaction. These variables vary by country. Therefore, educational policies and professional development programs tailored to each context are necessary to promote inquiry in these Ibero-American science education.

Keywords: inquiry, TIMSS, job satisfaction

Introduction

For decades, research in science education has advocated for the use of scientific inquiry to enhance students' scientific literacy. Many studies support a shift toward inquiry-based methods in teaching and learning (García-Carmona, 2020). Despite this, studies (Cañal et al., 2016; Romero-Ariza et al., 2019) show that teachers rarely use inquiry. Instead, they favor traditional methods, such as lectures, reliance on textbooks, and rote memorization. Hence, teachers' practices are far from the recommendations made by science education research (de Jong et al., 2024). This gap between educational policy and classroom reality is not unique to inquiry-based learning; similar discrepancies have been observed in the integration of Information and Communication Technologies (ICT) in science teaching, where reforms like the LOE and LOMCE in Spain have had limited impact on actual pedagogical practices (Yánez-Pérez et al., 2024a).

The limited adoption of inquiry is concerning, especially given its potential to foster deeper conceptual understanding, motivation, and scientific competencies (Lazonder & Harmsen, 2016; Aguilera & Perales-Palacios, 2020). Recent efforts to design digital tools, such as IndagApp, aim to lower the barriers to implementing inquiry by providing structured, curriculum-aligned resources that guide both teachers and students through the inquiry cycle (Yánez-Pérez et al., 2024b). However, the effectiveness of such tools depends on broader contextual factors that influence teachers' willingness and ability to change their practices. Therefore, this study seeks to identify the factors influencing the adoption of scientific inquiry in Primary Education across three Ibero-American contexts. The research question guiding this study is:

- What are the determinants of the adoption of inquiry by Primary Education teachers in Chile, Spain, and Portugal?

Theoretical Underpinnings

Inquiry is commonly defined as a teaching strategy where students generate and evaluate scientific explanations of the natural world while engaging in scientific practices and discussions. It involves analysing data and using evidence and logic to understand phenomena (Crawford,

2014; Schwartz et al., 2023). By adopting this approach, students learn science by mimicking the practices of real scientists. Based on the level of teacher support, four types of inquiry are identified in the literature (Vorholzer & von Aufschnaiter, 2019). At the lowest level, a confirmatory inquiry is one where the teacher provides the research question, procedure, and expected results. At the next level, students engage in structured inquiry, where the research question is unknown, but the teacher determines the question and procedure. Guided inquiry involves greater autonomy for students, who are only given the research question by the teacher. Finally, open inquiry allows students to select a phenomenon, formulate a research question, design an experimental procedure, and draw conclusions based on their findings.

These inquiry types align with the pedagogical cycle proposed by Pedaste et al. (2015), which includes phases such as orientation, conceptualization, investigation, conclusion, and discussion. Digital tools like IndagApp operationalize this cycle, offering scaffolded experiences that can help teachers transition from confirmatory to more open forms of inquiry (Yánez-Pérez et al., 2024b). However, the adoption of such innovative methodologies is often hindered by systemic barriers, including inadequate resources, limited professional development, and contextual school factors—issues also highlighted in studies on ICT integration in science education (Yánez-Pérez et al., 2024a).

Methodology

Participants

This study uses data from TIMSS 2019, which includes science teachers in 4th grade. Data were collected from three Ibero-American countries: Chile, Spain, and Portugal. TIMSS 2019 employed a stratified two-stage sampling method. In the first stage, schools were selected based on key variables: in Chile, by school type (public, subsidized private, private) and location (rural, urban); in Spain, by school type (public, semi-private, private) and bilingual status; and in Portugal, by school type (public, private), region, and size. In the second stage, intact classes within the selected schools were chosen. The study involved 169 schools in Chile (236 teachers), 181 in Portugal (314 teachers), and 501 in Spain (743 teachers).

Data Collection Instrument

The teacher questionnaire covered several constructs. This study focuses on the following: first, teacher professional development, measured by 4 items. Second, student preparation, which was assessed by asking teachers how eight factors limited their teaching of science. Examples include: “Students lacking prior knowledge or skills,” “Disruptive students,” and “Uninterested students.” Third, school climate and context, measured by 8 items such as "This school is located in a safe neighborhood" and "Students respect the school infrastructure." Fourth, the school’s emphasis on academic success, with items addressing teachers’ ability to inspire students and teachers’ expectations for student performance. Fifth, job satisfaction, measured by five items such as "I am enthusiastic about my work." Finally, the emphasis on inquiry-based science teaching, where teachers were asked how often they asked students to engage in eight inquiry-based practices.

We performed confirmatory factor analysis to assess the construct validity of the scales (results not shown), confirming their unidimensionality. Additionally, McDonald's Omega was calculated, showing that all scales demonstrated adequate internal consistency reliability ($\omega > 0.77$).

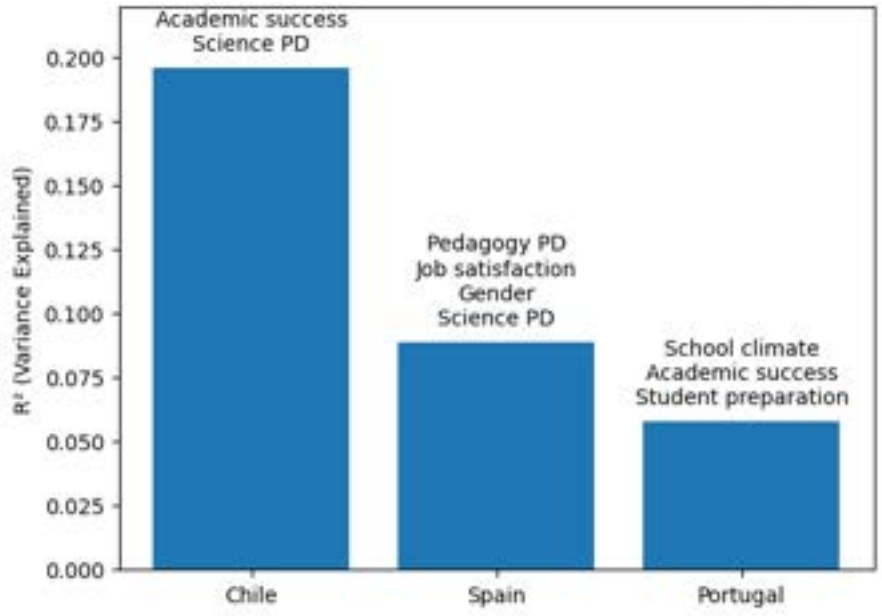
Data Analysis Procedure

Regression analysis was used to identify which factors collected in TIMSS 2019 were associated with teachers’ emphasis on inquiry-based science teaching.

Findings

The determinants of adopting scientific inquiry varied across countries (Figure 1).

Figure 1. Determinants per country



Note: Bars represent the total variance explained (R2) by the most predictive model in each country; text above each bar lists the key predictors included in that country's model, ordered conceptually.

In Chile, the most predictive model included two variables, with an $R^2 = .196$, $F(2, 135) = 16.17$, $p < .01$. The emphasis on academic success explained 13.6% of the variability in inquiry use, while professional development in the science curriculum explained an additional 6%. T-tests showed that teachers in schools with a strong emphasis on academic success adopted inquiry more ($M = 10.99$) than those in schools with less emphasis ($M = 9.75$), $t(143) = 3.74$, $p < .01$, with a large effect size ($d = 1.63$). Teachers who received training in the science curriculum ($M = 11.57$) also adopted more inquiry than those who did not ($M = 9.99$), $t(140) = 3.52$, $p < .01$, with a moderate effect size ($d = .76$).

In Spain, the most predictive model included four variables, with $R^2 = .089$, $F(4, 463) = 11.20$, $p < .01$. Professional development in pedagogy/instruction explained 4.7% of the variability, job satisfaction 2%, gender 1.2%, and professional development in the science curriculum 1.1%. T-tests revealed that teachers with training in pedagogy/instruction ($M = 9.91$) adopted more inquiry than those without training ($M = 9.04$), $t(486) = 4.52$, $p < .01$, with a moderate effect size ($d = .45$). Teachers with high job satisfaction ($M = 9.53$) also adopted more inquiry than those with low satisfaction ($M = 9.07$), $t(489) = 2.60$, $p = .01$, with a small effect size ($d = .24$). Men ($M = 9.59$) adopted more inquiry than women ($M = 9.17$), $t(488) = 2.10$, $p = .04$, with a small effect size ($d = .22$). Teachers with training in the science curriculum ($M = 10.03$) adopted more inquiry than those without it ($M = 9.13$), $t(483) = 3.95$, $p < .01$, with a moderate effect size ($d = .47$).

In Portugal, the most predictive model included three variables, with $R^2 = .058$, $F(3, 290) = 5.84$, $p < .01$. School climate explained 2.3% of the variability, academic success emphasis 2.1%, and student preparation 1.4%. T-tests showed a trend, though not significant, that teachers in schools with a safe school climate ($M = 9.54$) adopted less inquiry than those in less safe schools ($M = 10.14$), $t(304) = 2$, $p = .05$. No significant differences were found between teachers in schools with high or low emphasis on academic success or between those who perceived limitations due to student preparation.

Discussion

Research in science education and curriculum reforms advocates for the early adoption of inquiry-based methods (Crawford, 2014; de Jong et al., 2024; García-Carmona, 2020). However, few teachers implement this strategy (Romero-Ariza et al., 2019). This study identifies the factors influencing the adoption of inquiry in Chile, Spain, and Portugal, showing that these factors vary by country. In Chile, academic success emphasis and teacher training in the science curriculum are key. In Spain, pedagogical and curricular training, gender, and job satisfaction influence adoption. In Portugal, school climate, academic success emphasis, and student preparation are important, though not conclusive.

These findings align with previous research highlighting the contextual nature of educational innovations. For instance, Yánez-Pérez et al. (2024a) found that the integration of ICT in Spanish science classrooms under the LOE and LOMCE reforms was limited, and that teacher participation in continuous professional development was a significant predictor of ICT use. Findings also suggest that the availability of educational resources for inquiry teaching (e.g., Yánez-Pérez et al., 2024b) might be not enough, and specific measures should be developed to reduce logistical and pedagogical barriers to inquiry. Hence, as our results show, the effectiveness of such tools may be mediated by broader systemic factors such as school climate, job satisfaction, and institutional support.

These findings have significant implications for education. Interventions must be tailored to the specific needs of each country. In Chile, promoting academic success and enhancing teachers' knowledge of the science curriculum is essential. In Spain, more pedagogical and curricular training is needed, along with improving working conditions to increase job satisfaction. In Portugal, improving school climate, student preparation, and academic success emphasis are key. Though challenging, these measures are crucial to promoting the adoption of inquiry in science teaching. Future research should explore how digital tools like IndagApp can be embedded within supportive professional development programs that address the specific contextual variables identified in each country.

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Several Reasons To Develop Symbols In Physics Education

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Despite extensive research on conceptual change in physics education, comparatively less attention has been paid to the role of domain-specific networks underlying learning. This paper contributes to this area by applying the Theory of the Five Pillars of the Mind, which conceptualises learning as supported by five interconnected domain-specific networks: symbols, patterns, order, categories, and relationships, to physics education. In this study, we approach physics education through a Pillars framework, used both for the design of learning materials and for analysing pupils' learning outcomes with emphasis on symbols in physics education. Based on the literature and initial results, we identify several reasons to support the development of symbols in physics education. A novel approach was used to qualitatively analyse pupils' written responses, interpreted through the Pillars of the Mind framework, which indicates differences in representational use and conceptual reasoning. These results highlight the importance of analysing learning beyond performance scores and the central importance of symbols in physics education.

Keywords: symbols in physics education, error pattern analysis, pillars framework

Introduction

The theories of physics education investigate, among other topics, the cognitive processes involved in learning physics, including how pupils acquire and apply knowledge, for example, when learning Newton's second law. In a well-designed educational environment, pupils, as members of peer groups, are continuously exposed to numerous stimuli that their brains must process in real time. Sensory information is selectively filtered through prior knowledge and experience, with certain elements undergoing deeper cognitive processing. In teaching, specific learning situations are deliberately designed to serve as stimuli capable of resonating with pupils' current understanding.

Research on domain-specific networks remains relatively underexplored in physics education compared to the extensive literature on conceptual change. This paper addresses this gap by drawing on the Theory of the Five Pillars of the Mind (Tokuhama-Espinosa, 2019), which conceptualises learning as supported by five domain-specific networks: symbols, patterns, order, categories, and relationships. These networks are proposed as foundational for learning across domains and are grounded in cognitive neuroscience. To our knowledge, no studies explicitly apply this theory to physics education, although some elements can be found implicitly in textbooks, such as those from the International Baccalaureate (IB) Middle Years Programme (MYP).

This project aims to make these implicit structures explicit by designing learning materials that foster their development. Rather than focusing on content selection, we explore the learning activities and cognitive processes that promote understanding, and how this knowledge can optimise physics instruction. We applied the Pillars framework to design a fluid mechanics course for 15-year-old pupils. This contribution presents evidence for the importance of symbols in physics education through a review of the literature, an analysis of traditional learning materials, and an examination of pupils' incorrect responses in a written summative assessment, all of which we interpret within the proposed framework.

Theoretical Background

The design of learning materials used in everyday classrooms is highly influenced by many variables and can significantly impact pupils' ability to master the selected topic. Pupils' initial interests should be captured (Morkel, & Singh, 2024) to master the topic. Moreover, the arrangement of activities significantly influences pupils' learning, and it may differ across groups of pupils. In our research, we use the theory of the Five Pillars of the Mind (Tokuhama-Espinosa, 2019) as a theoretical framework to examine pupils' learning of selected physics topics. Sands (2021) adopted a similar approach, using sensemaking to formulate a theory of modelling in physics education. In this contribution, we focus on the role of symbols in physics education, which arises from the application of a framework supported by neuroscientific studies.

Benefits resulting from applications of relevant outputs of cognitive neuroscience or neuroscience in general have already been proven. Our research is grounded in the findings of Fynes-Clinton et al. (2022), Bowers (2016), Donoghue and Horvath (2016), Clement and Lovat (2012), Gkintoni and Dimakos (2022), and Immordino-Yang (2011). Some researchers focus on pupils with special needs and gifted pupils and offer interesting insights applicable also to every pupil, e.g., Sirois et al. (2008). The transformative role of neuroscience in school education is extensively discussed by Carew and Magsamen (2010), who highlight the potential of applying neuroscience knowledge to the development of teaching and learning methods and curriculum design. Some authors go further and examine teaching-learning methods and strategies, such as Elouafi, Lotfi, and Talbi (2021) and Owens and Tanner (2017).

Neuroconstructivism

The well-known concept from the learning sciences – constructivism – is closely linked to neuroscience. Westermann et al. (2007) introduced the term neuroconstructivism, which builds on earlier versions of constructivism and explains its key features based on insights into brain function. This term is further evolved by Renouard and Mazabraud (2018), Tokuhama-Espinosa and Borja (2023), and Mason, Schumacher, and Just (2021).

The constructivist part of the radical neuroconstructivist framework implies that 'to construct new learning, people build on previous knowledge using the foundation of the core notions' (Solis-Stovall, 2020) and when combined with "neuro- "approach, it views learning as 'the physical scaffolding of core notions and conceptual change that influence the emergence of mental representations in postnatal development' (Tokuhama-Espinosa, & Borja, 2023). Core concepts serve as prerequisite knowledge at every stage of learning, with each successive level of understanding building on those established at earlier stages. (Sporns, 2022) Therefore, as Tokuhama-Espinosa and Borja state, neuroconstructivism posits that foundational concepts must be acquired before more complex ideas can be developed, with learning progressing in a neurophysiological way, in which primary neural networks are established first, providing a scaffold for secondary networks to build upon. While radical constructivism suggests that context influences one's ability to learn, the radical aspect of the radical neuroconstructivist framework incorporates meaning-making, which is highly influenced by the learner's individuality. The Theory of Five Pillars of the Mind is grounded in radical neuroconstructivism.

The Pillars Framework

A research team led by Tokuhama-Espinosa reviewed approximately 1,000 neuroscientific studies investigating brain processes underlying learning mathematics and language. They aimed to categorise these processes based on the brain regions activated during these activities. This

effort resulted in the Theory of Five Pillars of the Mind, which identifies five fundamental domain-specific networks: symbols, patterns, order, categories, and relationships. These domain-specific networks overlap significantly between math and language (Caravolas et al., 2012). Even though learning maths and languages involves domain-specific networks, learning depends on general cognitive abilities, including attention, memory, and executive function (especially inhibitory control, cognitive flexibility, and working memory). Tokuhama-Espinosa and Borja (2023) further analyse math learning pathways using a radical neuroconstructivist approach, meaning they identify the core notions that are essentially pathways of domain-specific networks.

Each of these domain-specific network groups, called a pillar, has subpillars. We have already been researching the application of this theory to physics education in several domains. Some of the most important results of this research have been published in the *Journal of Baltic Science Education* (Demkanin, Červeňová, & Sands, 2025), *Digital* (Červeňová, & Demkanin, 2025a), and *Girep-Epec conference proceedings* (Červeňová, & Demkanin, 2025b). We have identified significant overlaps between this theory and established theories of physics education, analysed selected physics learning materials, and designed learning materials on fluid mechanics using this framework. Designed learning materials were implemented in the everyday classroom, and their effectiveness was evaluated in a quasi-experimental design and proven valid for everyday use, with significant changes in conceptual understanding of Fluid Mechanics compared to the control group.

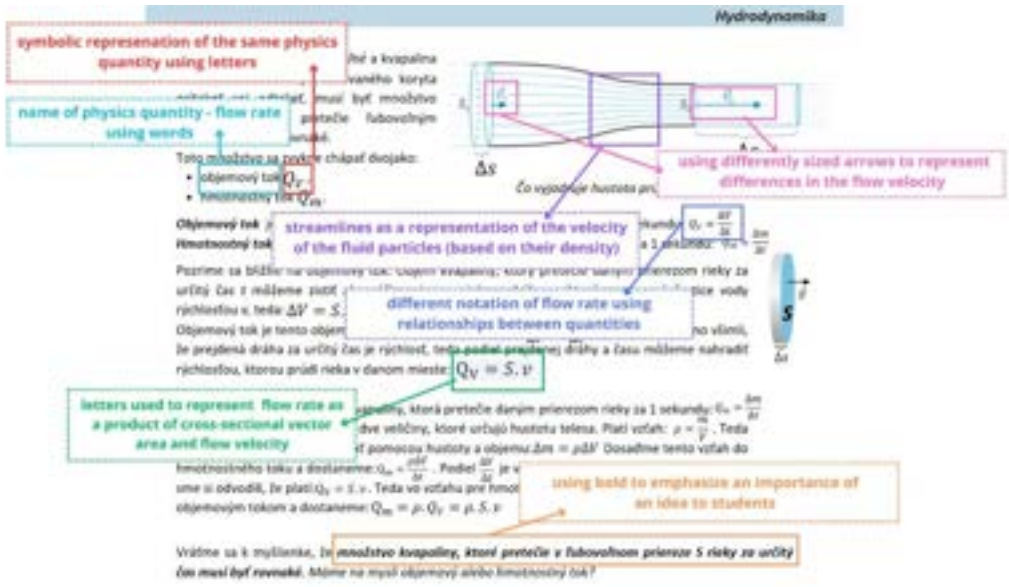
Symbols

In this contribution, we focus specifically on pillar symbols. Symbols are defined by Tokuhama-Espinosa (2019) as 'characters used in place of conventional representations to signify meanings, functions, processes, feelings, or objects, including words. A symbol can be a simple mark or letter, but it can also be an emoji or ideogram; anything that stands for something else, including emblems, street signals, company logos, and other visible signs.' (Tokuhama-Espinosa, 2019) Symbols can also be abstract concepts. Symbols further divide into forms, shapes, and representations.

Given the aim of this research, Figure 1 presents an example of an analysis of physics learning material, focusing on identifying symbols in a short section of the material. This learning material has been designed using the Pillars theory as a framework. This section is about flow rate and the continuity equation. The language of this short part is Slovak, but most people can understand the highlighted symbols, since physics uses a unified symbolic language despite small variations in symbols; for example, the function tangent is noted as tg(x) in Slovakia, whereas in other countries tan(x) is commonly used.

Symbols, as mentioned above, are used to represent a concept or a physics quantity. For example, one can use letters (Q_V), words ('objemový tok'), and relationships to represent the same quantity – flow rate. Symbols contain information about the quantity they represent, e.g., using different-sized arrows to illustrate the difference in the magnitude of flow velocity in the different places of a pipe. Streamlines are a symbolic representation of a flow that conveys information about the velocity of fluid particles, based on the density of streamlines at each point in the flow. On the other hand, symbols can be used to communicate between the author of the learning material and the pupils. Authors of learning materials often use bold to emphasise the importance of an idea to pupils.

Figure 1. Examples of symbols in the learning materials – flow rate.



Symbols in theories of physics education and cognitive science

The development of symbols in physics education can be supported by findings from cognitive neuroscience showing partial overlaps between neural systems involved in language and mathematical symbol processing, e.g., (Dehaene, 2011), or (Dehaene, & Cohen, 2010). Behavioral studies of literacy development further demonstrate that learning symbols relies on robust domain-general cognitive predictors across languages (Caravolas et al., 2012). We consider the evidence of overlapping brain areas corresponding to symbolic representations of language and math (Dehaene, 2007; 2009; Dehaene et al., 2015) to strongly support the 'why' of the development of symbols in physics education. Based on the studies mentioned, we presume that the development of symbols in physics supports the learner's ability to process, understand, and manipulate symbols across different subjects.

Strategic development of symbols in everyday physics classrooms can help reduce the cognitive load pupils experience daily when solving physics problems. Pass and Merriënboer (2020) discuss effective methods for managing working memory load in the learning of complex tasks. Some of the methods involve structuring complex information, guiding learners, and strategically integrating visual and symbolic representations to reduce cognitive load.

Multiple representations are connected to a property of the nervous system called redundancy, which means that different configurations of cellular and synaptic components enable the same neural circuit functions. (Mizusaki, & O'Donnell, 2021). This property of the nervous system contributes to the robustness of brain functions by enabling alternative neural pathways to compensate when a particular pathway is damaged or disrupted. Neural representations and their associations are formed through learning. Each object is represented by distributed networks of neurons, in which neural activity is also distributed. This is referred to as distributed representation (Rybár, Beňušková, & Kvasnička, 2002). In other words, the brain stores multiple representations of the same concept across different neural networks as a result of learning. When distributed representations of a given physics concept are established, forgetting tends to occur gradually. When multiple representations are also coherent, conceptual change could be facilitated by linking new and prior knowledge. Symbols are also essential for dual coding (Clark & Paivio, 1991), in which visual and written representations are paired, and they promote the development of correct models when the representations are correct.

Methodology

In this contribution, we primarily present reasons for supporting the development of symbols in physics education. Some of these reasons are grounded in existing literature and are mentioned in the theoretical background, while others emerge from the presented research. In the methodology, we will describe parts of the research relevant to the topic of this contribution. The main goal of our research concerning physics learning material was to identify the extent to which the Pillars are developed in physics education. We identified intermediate objectives, which were:

- to identify the extent to which the Pillars are developed in physics learning materials concerning the inclined plane and fluid mechanics;
- to apply the Pillars framework for the analysis of pupils' errors in the physics summative exam.

Research Sample

Research Sample For Pupils' Error Analysis

In this contribution, we focused mostly on the analysis of pupils' errors in a summative test using the Pillars framework. We conducted a quasi-experiment with a research sample of 26 pupils aged 15-16 and a control group of 27 pupils aged 15-16. The researcher taught the pupils in the research group, while those in the control group were taught by a teacher with over 30 years of experience teaching physics. Assignment to groups was not random. Both research and control groups were assigned a summative assessment concerning three physics topics: fluid mechanics (research topic), gravitational field, and rigid body. The difference between the research and the control group was in the learning materials on fluid mechanics used in the classroom. Pupils in the research group were given designed learning materials using the Pillars framework that aimed to foster the development of the Pillars more uniformly than identified in the existing learning materials. In contrast, pupils in the control group used traditional learning materials. The design and initial implementation of the designed learning materials were published in GIREP-EPEC 23 proceedings (Červeňová, & Demkanin, 2025b).

Research Sample For Analysis Of The Learning Materials

For the initial analysis of the learning materials using the Pillars framework, we selected several physics textbooks to identify the key concepts developed in them. For each concept, a pillar was allocated based on the context in the analysed textbooks. We defined selection criteria for textbook analysis as follows:

- alignment with national requirements for higher education physics graduates;
- market usage of textbooks;
- similarity of pedagogical approach.

Selected textbooks Duncan and Kennett (2014), Morris (2015), Reynolds (2013), Koubek et al. (2009), and Lapitková et al. (2012) all discuss prerequisites and selected topics. They were chosen because they align with the Slovak national requirements. Koubek et al. (2009) and Lapitková et al. (2012) are widely used in Slovakia and approved by the Ministry of Education. Duncan and Kennett (2014), Morris (2015), and Reynolds (2013) are widely used in general and within selected topics, aligning with national requirements. Parts of these textbooks discussing either inclined plane or fluid mechanics constituted our dataset.

Methods Used

Pupils' Error Analysis

In this contribution, we do not focus on overall results comparing the research and control group using different metrics (pre-test, post-test, follow-up test, and summative assessments), but rather on the analysis of errors pupils made in the summative written assessment using the Pillars framework. We believe such analysis will provide insights not only into how Pillars support learning (along with analysis of the learning materials), but also into how the underdevelopment of each domain-specific network influences learning outcomes. In our broader research, we have employed several measurement tools, including recordings of classes, open-ended questions aimed at pupils' initial ideas in a questionnaire, repeated measurements (pre-test, post-test, and follow-up test), and a summative written final assignment. We view pupils as holons, but due to the page limits of this contribution, we will discuss only the results of the qualitative analysis of pupils' mistakes in a summative written assignment.

This assignment consists of two parts: multiple-choice questions aimed at both theory and application, and open-ended theoretical and computational questions. The first part of the written exam is assigned to pupils for 30 minutes and is immediately followed by the second open-ended question part, which is planned for up to 90 minutes. Pupils in the research and control groups were given the same assignment simultaneously. Their answers were then analysed by the researcher and the teacher of the control group using the same marking scheme, followed by analysis of the pupils' answers with a success rate below 50%. For each error, we identified where a pupil could have failed when trying to answer the question by using the Pillars framework.

Analysis Of The Learning Materials

The analysis of the learning materials and the identification of the Pillars were conducted individually by two researchers using MAXQDA24, who coded selected parts of the textbooks. Our coding scheme comprised the Pillars themselves, and the specific code for each pillar was used to code the parts of the textbooks that potentially fostered the development of that pillar. The agreement rate among researchers was 86%, and the final dataset reflected the agreed-upon content in the discussion. Analysing four series of physics textbooks led to the identification of examples for each pillar across physics topics and several observations.

Findings

Table 1. Results of initial analysis of the learning materials using the Pillars framework.

Pillar	Discussed topic	N (%)
Symbols	Inclined plane	**7 (50%)**
	Fluid mechanics	**6 (54.5%)**
Patterns	Inclined plane	4 (28.6%)
	Fluid mechanics	3 (27.3%)
Order	Inclined plane	4 (28.6%)
	Fluid mechanics	2 (18.2%)
Categories	Inclined plane	4 (28.6%)
	Fluid mechanics	1 (9.1%)
Relationships	Inclined plane	**8 (57%)**
	Fluid mechanics	**8 (72.3%)**

This contribution is focused on the reasons for developing symbols in physics education. Along with the reasons identified in the literature, we further identified evidence from data collected in pupils' everyday classroom settings. Firstly, we present results of initial analysis of the learning materials using the Pillars framework, followed by the results of analysing pupils' mistakes in the summative written exam.

Table 1 shows the results of the initial analysis of the learning materials concerning the topics inclined plane and fluid mechanics. Results indicate that the most frequently emphasised Pillars in the existing physics learning materials on these topics are symbols and relationships. Although this phenomenon requires further examination in a larger dataset, it aligns epistemologically with existing theories of physics education, which emphasise remembering, understanding, and manipulating symbols as important aims of physics education, along with the relationships between symbols. In existing theories, relationships are viewed as expressing how quantities are related to predict outcomes in response to changes in variables or to understand an observed phenomenon. However, in the Pillars framework, relationships are domain-specific networks that cover not only calculative core notions, but also core notions responsible for measurements, or science process skills. Symbols are also domain-specific networks responsible for several core notions, not only for remembering symbolic representations of physics quantities, but also, for example, different representations of relationships, such as graphs.

Outcomes Of The Analysis Of The Pupils' Mistakes In The Written Summative Exam

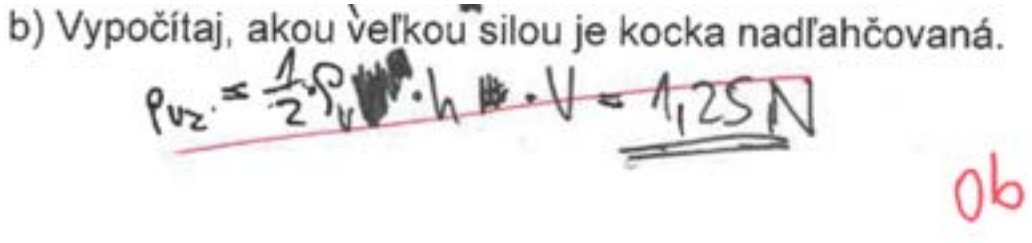
Data obtained from the summative written exam administered to both the control and research groups were analysed statistically, and the results were presented at the GIREP-EPEC 2025 conference. In this contribution, we focused on the qualitative analysis of pupils' answers with emphasis on the errors they made. We analysed the answers with errors and a success rate lower than 50%.

Figure 2. An example of pupils' errors in a written summative exam – flow rate.



Figure 2 and Figure 3 show examples of errors pupils made in the written summative exam taken at the end of a semester. Both of these examples are concerning the topic of Fluid mechanics, while Figure 2 shows a task where a pupil should determine the flow rate from given fluid velocity and surface of the pipe, Figure 3 shows a task requiring a calculation of a buoyant force acting on a granite cube, when given the side length of this cube and density of the water it has been inserted in. An error depicted in Figure 2 is identified by researchers as a failure to apply the correct relationship for the flow rate and to understand the symbols used in that relationship, as in Bernoulli's equation, where velocity (v) is present. A pupil probably could not even identify which variables (their symbolic representations) are given in the task or how to use the information to solve it. Figure 3 shows that the pupil did not know the symbolic representation of buoyant force (F_{vz}) and did not know the relationship for the buoyant force. The relationship this pupil wrote was likely a mix of Bernoulli's equation, a hydrostatic pressure relationship, and a buoyant force relationship.

Figure 3. An example of pupils' errors in a written summative exam – buoyant force.



The qualitative analysis of data using the Pillars framework has resulted in several observations:

O1. Pupils mostly failed in the domains of relationships, symbols, or patterns.

O2. When pupils failed in the relationships domain, it was mostly because they did not remember the dependency between variables or were unable to apply it correctly.

O3. When failing in the patterns domain, they could not proceed with the task correctly.

O4. Errors associated with the inability to proceed with the task in the symbols domain were most often assigned a success rate 0%.

O5. Manipulation with symbols does not require understanding of those symbols.

During data analysis, several responses contained no written work and therefore could not be analysed further due to insufficient data. The observations reported above are based solely on responses that included pupils' written notes and expressed ideas. Observation O1 is consistent with the results of the analysis of the selected learning materials and aligns with theories in physics education, which emphasize the central role of symbols and relationships. Nevertheless, pupils continue to experience difficulties in these domains, highlighting their critical importance in physics education. Interestingly, deficiencies were also identified in the domain of patterns, which appeared underdeveloped and contributed to the observed errors. This may be attributed to a lack of explicit and intentional focus on pattern development in physics instruction.

Errors identified by the researchers as belonging to the symbols domain were primarily due to a lack of coherent understanding of both the written formulation of the task and its visual representation. Pupils frequently recalled symbols commonly used in fluid mechanics; however, they often did not demonstrate an understanding of their meanings. Although the relationships domain was identified most frequently, the symbols domain was most strongly associated with a 0% success rate. The analysis across responses further showed that pupils often manipulated symbols without a demonstrated understanding of what those symbols represented.

Conclusions And Discussion

This study aimed to provide converging evidence on the importance of symbols in physics education, drawing on both literature and research. We examined pupils' errors in the written summative physics exam alongside selected learning materials using the Pillars framework. The analysis of pupils' responses showed that symbols were frequently recalled and used, yet often without demonstrated understanding of their meaning. Errors associated with the symbols domain were most consistently linked to unsuccessful problem solving, with a 0% success rate. These findings suggest that difficulties with symbols are not primarily related to a lack of exposure, but rather to insufficient development of meaningful symbolic understanding. These results are epistemologically aligned with existing theories in physics education, which emphasise remembering, understanding, and manipulating symbols—and the relationships between them—as key aims of physics education. The textbook analysis further supports this alignment, as

symbols and relationships were identified as the most strongly fostered domains in the analysed learning materials.

From the perspective of cognitive neuroscience, the importance of symbols in physics learning is further supported by findings indicating partial overlap between neural systems involved in language symbol processing and mathematical symbol processing. On this basis, it can be presumed that the development of symbols in physics may support learners' ability to process, understand, and manipulate symbols across different subject domains. Strategic and explicit development of symbols in everyday physics classrooms may therefore help reduce the cognitive load pupils experience when solving physics problems.

The role of symbols is also closely connected to the use of multiple representations, which correspond to redundancy. When distributed representations of a physics concept are established, forgetting tends to occur more gradually. Furthermore, when multiple representations are coherent, conceptual change may be facilitated by linking new knowledge with prior knowledge. In this context, symbols play an important role. In addition, symbols are essential for dual coding, which has been shown to support the construction of mental models when the representations involved are conceptually accurate and mutually consistent. The prevalence of symbol-related errors identified in this study, therefore, highlights the risk that poorly understood or weakly integrated symbols may contribute to the development of inadequate mental models.

Taken together, the findings from pupils' error analysis, textbook analysis, and existing literature suggest that symbols are not merely formal tools for calculation, but central cognitive and epistemic components in physics learning. These results underscore the need for instructional approaches that explicitly and intentionally develop symbols as a core objective of physics education. Future research may build on these findings by investigating instructional interventions that systematically target the development of symbols domain and by examining how this development interacts with learning across different physics topics and educational levels.

Several limitations of the presented study should be acknowledged and addressed in future research. One limitation concerns the limited interpretability of pupils' responses to multiple-choice questions, as their reasoning may be influenced or constrained by the provided answer options, particularly when incorrect responses are selected with no other notes of the pupils' thinking. While open-ended questions were included in the study, they did not directly elaborate on the corresponding multiple-choice items and, therefore, offered limited insights into the underlying reasoning processes associated with those responses. In addition, pupils' written answers represent observable outcomes of learning that are shaped by numerous, largely uncontrollable variables inherent to everyday classroom contexts. As a result, these responses may not fully reflect pupils' true conceptual understanding.

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ESERA 2025 Copenhagen

A Structured Framework For Designing Syllabus-Focused Educational Escape Rooms (EERs) That Promote The Development Of Students' 4C Skills.

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Educational Escape Rooms (EERs) have gained recognition as an innovative pedagogical approach that enhances student engagement and learning by integrating game-based elements, collaborative problem-solving, and even inquiry-driven activities. By leveraging immersive narratives, puzzles, and teamwork, EERs provide a dynamic environment that fosters both subject knowledge acquisition and essential 21st-century skills, particularly the 4Cs - Critical Thinking, Creativity, Collaboration, and Communication.

This study introduces a structured framework for designing syllabus-aligned EERs that effectively integrate learning objectives with engaging, interactive experiences. Grounded in the Learning Environment, Learning Processes, and Learning Outcomes (LEPO) framework, the proposed model emphasizes key design principles, including real-world relevance, active learning strategies, and scaffolded challenges. The framework highlights how well-designed EERs can enhance cognitive, affective, and psychomotor learning outcomes while promoting autonomy, motivation, and deeper conceptual understanding.

By offering a research-based and adaptable design strategy, this study provides educators with practical guidance on developing effective EER activities across diverse educational settings. This work contributes to the broader discourse on game-based learning and curriculum innovation, equipping educators with tools to create engaging and meaningful learning experiences that cultivate both disciplinary knowledge and essential future-ready skills.

Keywords: Classroom practices, Collaborative learning, Instructional design

Introduction And Theoretical Background

Educational Escape Rooms (EERs)

Educational Escape Rooms (EERs) can be defined as a game-based learning approach that uses problem-based techniques that push students to think critically and creatively while incorporating game features (theme-story, puzzles, and activities to advance). EERs have become a viable substitute for traditional methods of promoting students' conceptual and skill-based learning (Nicholson, 2018). These emerging educational tools exhibit inherent design versatility and are capable of integrating diverse elements of effective learning (e.g., collaborative learning space, challenging tasks, real-world context, supportive environment, hands-on activities). Moreover, they are compatible with several theoretical frameworks (e.g., self-determination and self-efficacy motivational theories, experiential and inquiry-based learning approaches), each offering unique insights into their design and implementation to enhance specific learning processes (see Table 1). Focusing on their ability to promote the practice and development of 21st century skills, like the 4Cs (Villias & Winterbottom, 2024), along with content knowledge, this study attempts to develop an appropriate design framework for this cause.

Table 1. Theoretical underpinnings' connection to EER activities' learning mechanism

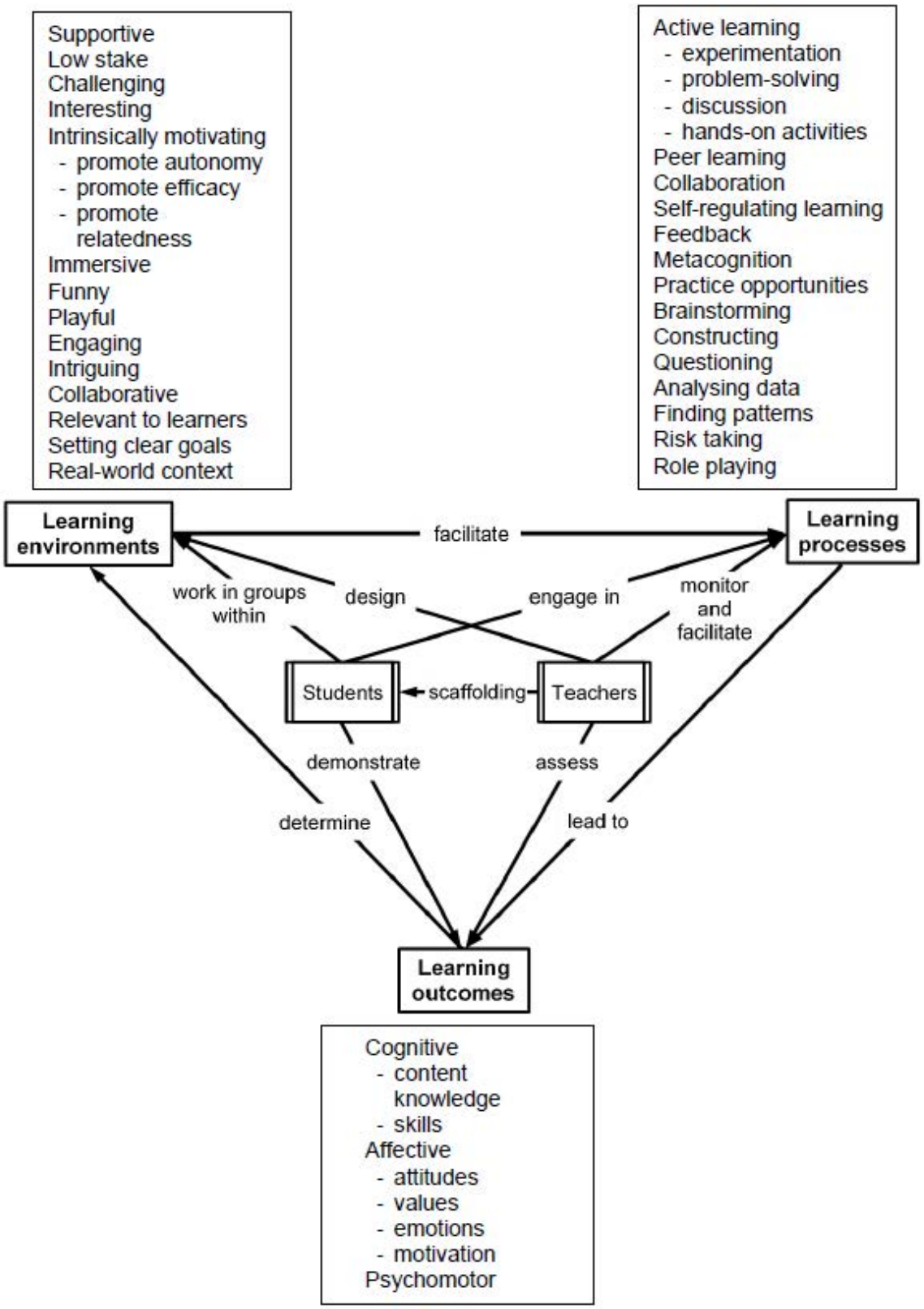
Theoretical frameworks	Elements of effective learning
Motivational theories • Self-Determination theory • Self-efficacy theory • Goal-setting theory	Players in control (autonomous) Adapted challenge (competence) Peer collaboration (relatedness) Relevant to learners' interests (intrinsic motivation) Escalating difficulty (mastery experience) Observing others (vicarious experience) Facilitator's and peers' encouragement (verbal persuasion) Relaxed, risk-free environment (physical/emotional state) Setting clear goals Providing direct feedback
Game-based learning	Playful environment (fun) Interesting (curiosity) Intriguing (discovery) Adapted challenge (competence) Setting clear goals Players in control Collaborative (social interaction) Providing direct feedback Low-stake failure Engaging Immersive (flow-like experience)
Experiential learning	Learning by doing (active learning) Hands-on activities Experimentation Problem-solving Discussion Real-world context Collaborative and social environment Reflection (debriefing)
Problem-based learning	Real-world context Collaborative environment Discussion (conversation space) Questioning Brainstorming Metacognition Peer learning Scaffolding
Inquiry-based learning	Interesting (curiosity) Collaborative social environment Discussion Problem-solving Scaffolding Experimentation Questioning

Materials And Methods

A Conceptual Framework of Learning with EERs

Adopting a generalised conceptual and integrated framework of learning, the LEPO framework (Phillips, McNaught, & Kennedy, 2010), and adapting it appropriately to showcase the unique characteristics that EER activities encapsulate, I present below a model that reveals the interrelationships between its basic components (see Figure 1).

Figure 1. Model of the conceptual framework of learning with EERs (adapted from Phillips, McNaught, & Kennedy, 2010, p. 2498).



Dependent on the learning processes being facilitated within EERs' learning environment, different learning outcomes can be produced. For example, debriefing sessions contribute to content learning (Veldkamp, 2022), while problem-solving improves learners' critical thinking skills (Kek & Huijser, 2011). Therefore, when designing an EER learning activity all these components must be considered: the learning environment where students work in, the learning processes they engage in, and the desired learning outcomes they are expected to demonstrate. Key attributes of these components, as informed by the theoretical underpinnings of EERs, are provided in adjacent boxes (see Figure 1). The first box summarises the features of an effective learning environment. The second box lists various learning processes that can be facilitated during the implementation of an EER activity. Lastly, the third box categorises expected learning outcomes based on Bloom's taxonomy across three domains: cognitive, affective, and psychomotor.

Placing a different level of emphasis on these properties while designing an EER should align with the intended learning outcomes of the intervention. For example:

a) *Prioritising the development of social skills* can be supported through the inclusion of collaborative learning activities.

b) *Enhancing science learning among disengaged or low-performing students* may involve tailoring the EER's theme to their interests while cultivating a supportive and playful learning environment.

c) *Developing learners' psychomotor (laboratory) skills* can be facilitated by providing structured practice opportunities and timely, direct feedback during experiments and other hands-on activities that require precision and coordination.

d) *Promoting environmental awareness and the adoption of sustainability values* can be strengthened by linking the EER's theme and narrative to real-world environmental challenges and situating learning within an immersive environment.

e) *Supporting conceptual understanding* may be achieved by integrating scaffolding mechanisms, such as guided prompts, visualisations, and adaptive hints that respond to learners' progress.

f) *Fostering motivation and engagement* can be enhanced through the use of meaningful challenges, clear progression pathways, and reward systems that acknowledge effort as well as achievement.

g) *Encouraging self-regulated learning* may involve incorporating goal-setting tools, reflective prompts, and opportunities for learners to monitor and adjust their own learning strategies.

h) *Developing critical thinking and problem-solving skills* can be supported by presenting open-ended tasks, ill-structured problems, and scenarios that require learners to evaluate evidence and make informed decisions.

Analyses And Findings

The Design Framework

Using this model as a reference point and concentrating on its particular components that, according to the available literature, are recognized to foster the advancement of the 4C's, I devised a dedicated design framework to guide the structuring of the EER activities in this study (see Figures 2a, 2b). Although the presented framework can serve as a foundation for the design of EER activities, each design should not solely adhere to the highlighted components of the

framework. Instead, additional elements can be incorporated to align each activity with its chosen learning objectives, theme, and content most effectively.

Figure 2a. Design framework for EERs that promote the 4C skills' development. Learning environment component.

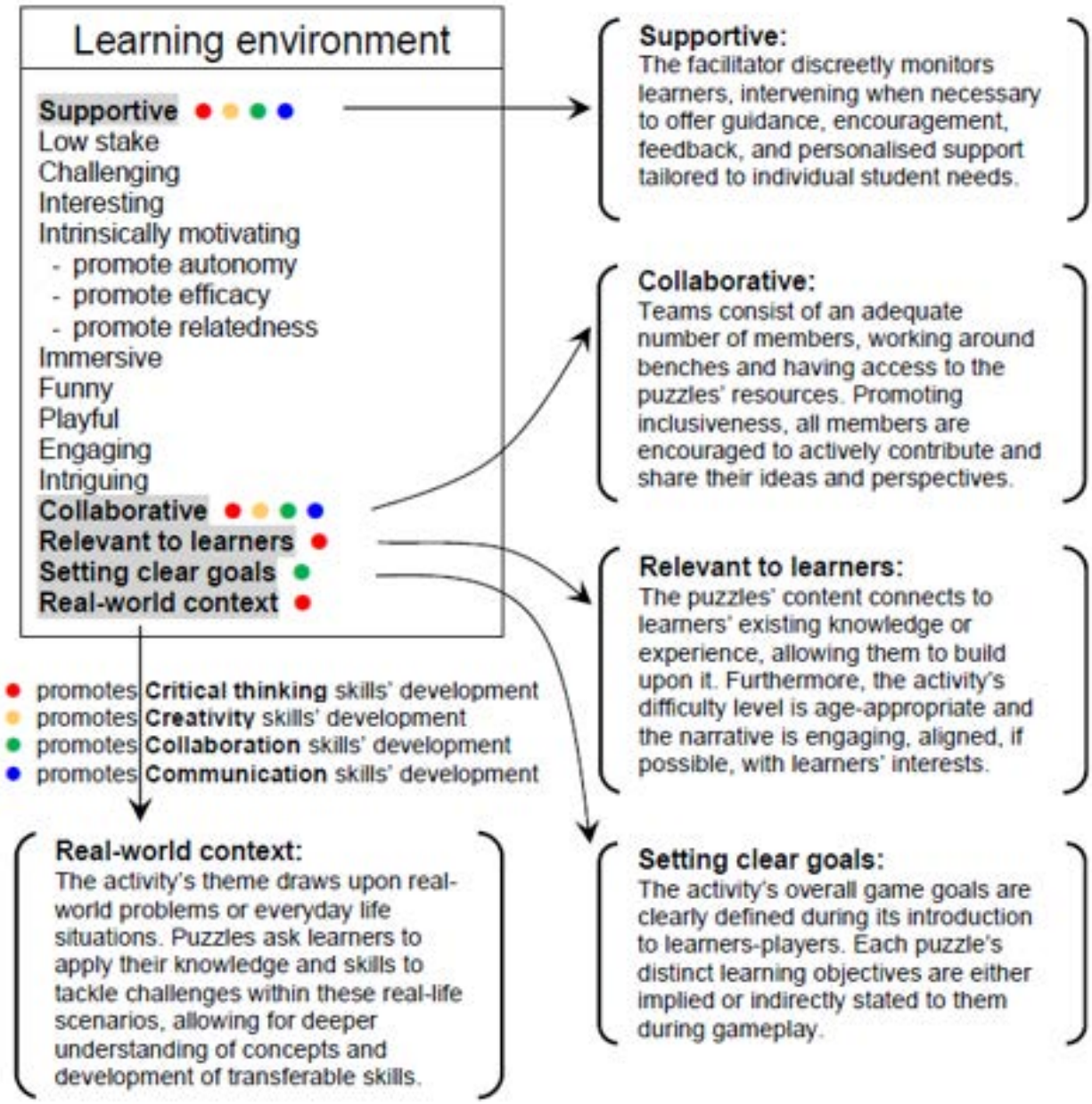
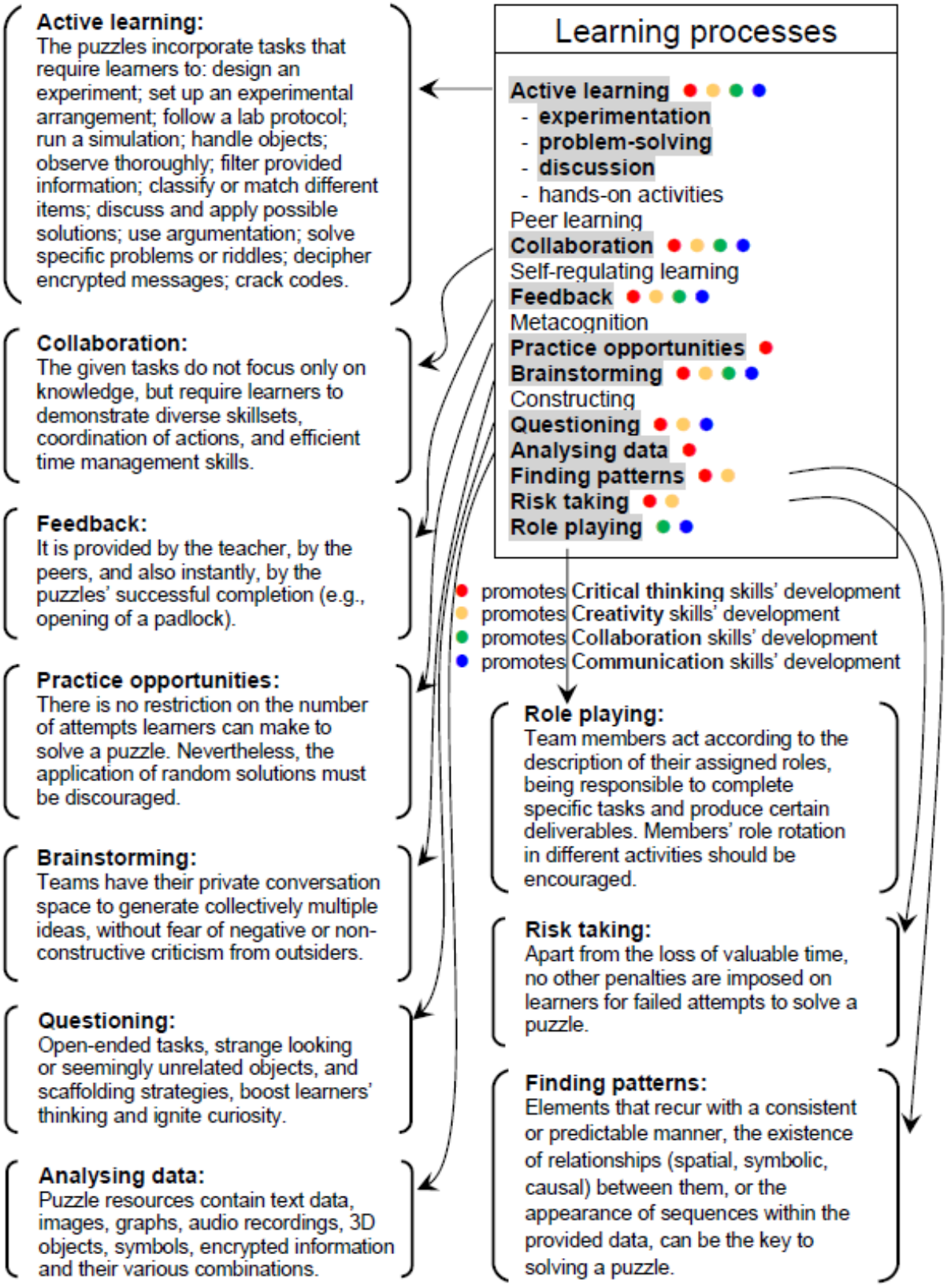


Figure 2b. Design framework for EERs that promote the 4C skills' development. Learning processes component.



Discussion

The presented conceptual and design framework of EERs can be used as a guide to prepare engaging learning activities that are capable of transforming the classroom's learning environment and promote students' active learning, advancing the theoretical grounding of EERs and offering practical advice to practitioners.

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A Teaching-Learning Sequence For Heat Transfer And Nature Of Scientific Inquiry At Primary Education

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The purpose of the present study was to describe and evaluate the pilot implementation of a Teaching–Learning Sequence (TLS) on the modes of heat transfer (conduction, convection, and radiation) and the Nature of Scientific Inquiry (NOSI) for primary school students. The description and evaluation, presented in this paper, focus on part of the taught knowledge, that is, students' understanding of heat transfer by conduction in metals (conceptual knowledge), selected aspects of the Control-of-Variables Strategy (procedural knowledge), and selected aspects of NOSI (epistemological knowledge). Data were collected through a written questionnaire administered before, during, and after instruction and were analysed using a mixed-methods approach. The results indicate a modest and gradual improvement across all three aspects of knowledge. The instructional design of the TLS supported the development of scientifically consistent conceptual understanding, informed procedural reasoning, and improved epistemological views related to scientific inquiry.

Keywords: heat transfer, nature of scientific inquiry, teaching-learning sequence

Introduction

Teaching–Learning Sequences (TLSs) refer to medium-scale curricula that are considered innovative research products. In a TLS, theories and approaches to teaching and learning are systematically integrated, enabling the design and implementation of theoretically informed and empirically grounded teaching–learning activities based on students' reasoning (Méheut & Psillos, 2004). The Model of Educational Reconstruction (MER) is a widely adopted methodological framework for the design and analysis of TLSs. Within the MER framework, the interaction between the results of empirical research on students' conceptions and learning processes and the didactic construction of scientific content is explicitly addressed (Duit et al., 2012).

The development of scientific literacy extends beyond the acquisition of scientific content knowledge and engagement with scientific practices, as it also involves understanding key aspects of the Nature of Science (NOS), with an emphasis on science as a distinct way of thinking and acting (Lederman et al., 2019). Within this framework, several researchers argue that science teaching should adopt a holistic approach, integrating conceptual, procedural, and epistemological learning objectives (Capps & Crawford, 2013). Moreover, fostering students' understanding of issues related to NOS is widely acknowledged as a central goal of science curricula worldwide (AAAS, 2011; NRC, 2011). Lederman et al. (2019) distinguish between NOS, which refers to the characteristics of scientific knowledge, and the Nature of Scientific Inquiry (NOSI), which refers to the characteristics of scientific practices, namely the processes through which scientific knowledge is generated. Although related, these two constructs are conceptually distinct. This distinction is considered pedagogically useful, as students' views of NOSI are generally more amenable to change than those of NOS (Kampourakis, 2016). Table 1 presents the eight aspects of NOSI proposed by Lederman et al. (2019) as instructional learning objectives.

Inquiry-based teaching is widely regarded as a suitable pedagogical framework for foregrounding and explicitly addressing aspects of NOSI (McComas et al., 2020). The purposeful integration of this approach into classroom practice enables students to engage with both scientific concepts and scientific inquiry processes, thereby supporting the development of a more informed understanding of NOSI-related issues (Lederman et al., 2019). At the same time, research indicates that improvements in students' conceptions of NOSI are associated with a deeper understanding of scientific concepts (Bächtold, 2024). Moreover, several inquiry practices have been identified as particularly effective in making NOSI aspects explicit during instruction, including: (a) identifying problems and formulating research questions, (b) managing and controlling variables, (c) constructing, using, and evaluating models, and (d) engaging in interaction and evidence-based argumentation around research findings (Bächtold, 2024).

Table 1. General aspects of NOSI (Lederman et al., 2019)

Aspect	Content
1	Scientific investigations all begin with a question, but do not necessarily test a hypothesis
2	There is no single set or sequence of steps followed in all investigations
3	Inquiry procedures are guided by the question asked
4	All scientists performing the same procedures may not get the same results
5	Inquiry procedures can influence results
6	Scientific data are not the same as scientific evidence
7	Research conclusions must be consistent with the data collected
8	Explanations are developed from a combination of collected data and what is already known

However, it should be noted that the mere implementation of inquiry-based teaching does not necessarily lead to the development of students' understanding of NOSI aspects (Concannon et al., 2020; Morell et al., 2024). Rather, research suggests that an explicit and reflective approach to the processes underlying inquiry-based instruction is required in order to foreground the relevant NOSI aspects embedded within these processes (Witucki et al., 2023). Akerson et al. (2019), synthesising the relevant literature on effective teaching and learning through reflective practices, identify the following as particularly important: (a) students' collaborative group work, (b) the use of teacher-posed reflective questions and subsequent whole-class discussion, (c) scaffolding students' thinking about NOSI, (d) students' engagement in hands-on activities, and (e) a gradual shift from structured to open inquiry.

At the primary education level, the teaching of heat transfer usually remains at a phenomenological level, without systematically confronting alternative ideas that hinder students' conceptual understanding of the phenomenon. In this context, a heat-flow model is often employed; although this model supports students' conceptualisation of abstract thermal concepts, it may simultaneously reinforce the alternative conception that heat has material properties (de Berg, 2006). At the same time, the literature emphasises the need to teach the three modes of heat transfer as conceptually distinct, as students often conflate them, particularly when distinguishing between conduction in metals and heat transfer in fluids (Çoruhlu, 2017). In parallel, it is essential for instruction to explicitly confront the alternative conception of heat as a substance, since this substance-based view negatively affects students' understanding of the modes of heat transfer. Within this broader instructional goal, targeted instruction on conduction, convection, and radiative heat transfer can further support the gradual conceptual change away from this alternative conception.

Methodology

The purpose of the present paper was to describe and evaluate the pilot implementation of a TLS on the modes of heat transfer (conduction, convection, and radiation) designed for primary school students, with a specific focus on selected aspects of the content and practices addressed, as justified below. The TLS integrates inquiry practices, specifically modelling and the Control-of-Variables Strategy (CVS), aiming to support students' understanding of the scientific content, the development of inquiry skills, and the conceptualisation of selected aspects of NOSI (Valkanou & Zoupidis, 2025). It is assumed that the integration of inquiry practices with the explicit and reflective teaching of the NOSI aspects highlighted through these practices enhances students' perceptions of these aspects, as well as their understanding of the scientific content intended to be taught.

The TLS was designed following the MER framework (Duit et al., 2012) and consisted of six instructional units, each with a duration of 90 minutes. The central instructional goals of the sequence were to support a clear distinction between the three modes of heat transfer (conduction, convection, and radiation) and the confrontation of students' alternative conception that heat has material properties (Valkanou et al., 2024b). Table 2 presents an overview of the thematic focus of each unit of the TLS, the inquiry practice integrated into each unit, and the NOSI aspects that were explicitly addressed through these practices.

Table 2. Units of the TLS, the inquiry practices integrated and NOSI aspects highlighted

Unit	Inquiry practice	NOSI aspect(s)
1: Measurements errors in experimental process	-	5^{th}
2: Explicit teaching of CVS	-	5^{th}
3: Heat conduction in metals	CVS	3^{rd}, 5^{th} & 7^{th}
4: Heat conduction in solid materials	CVS	3^{rd}, 5^{th} & 7^{th}
5: Heat convection	Modelling	3^{rd}, 7^{th} & 8^{th}
6: Heat transfer by radiation	CVS	3^{rd}, 5^{th}, 7^{th} & 8^{th}

Note: NOSI aspects are numbered according to Lederman et al. (2019): (3) Inquiry procedures are guided by the question asked; (5) Inquiry procedures can influence results; (7) Research conclusions must be consistent with the data collected; (8) Explanations are developed from a combination of collected data and what is already known.

In the present paper, we focus on the students' understanding of (a) heat transfer by conduction in metals (conceptual knowledge), (b) selected aspects of CVS reasoning (procedural knowledge), and (c) selected aspects of NOSI (epistemological knowledge), as a result of the TLS implementation. Specifically, the research question guiding this study was the following:

"To what extent did students' understanding of (a) heat transfer by conduction in metals, (b) the aspect of CVS reasoning related to distinguishing between valid and invalid experiments, and (c) the third aspect of NOSI namely that inquiry procedures are guided by the research question, improve following the TLS implementation?"

The Structure Of The First Three Units Of The TLS

In the present subsection, the focus is on the design of the first three units of the TLS, since the evaluation of the conceptual, procedural, and epistemological aspects presented in this paper is

primarily contingent upon students' engagement with these units. The first two units of the sequence functioned as introductory lessons prior to the core teaching, while the third unit constituted part of the main teaching and was designed based on the 5E instructional model (Ruiz-Martín & Bybee, 2022).

First unit

The aim of the first unit was the explicit instruction of students, regarding the management of measurement errors in experimental procedures. Previous research has shown that measurement errors and inconsistencies, observed during experimentation, significantly influence students' formulation of conclusions in instructional settings (Valkanou et al., 2024b). Moreover, primary school students are capable of recognising measurement uncertainty, and it is particularly beneficial for them to engage in activities involving multiple measurements for data collection and subsequent analysis (Munier et al., 2013).

Within this framework, this unit followed an uncertainty-oriented approach, aiming to raise students' awareness of these aspects of experimental practice. Specifically, students worked in groups and were asked to measure the length of an object using different measuring instruments. The goal was for them to realise that measurements are not identical, either among groups using the same measuring instruments or among groups using different ones. Subsequently, the teacher explicitly introduced the concept of the mean value, explaining that one way to reduce measurement error is to perform multiple measurements and calculate their average. Through these activities, students were expected to recognise that data collection methods can influence the conclusions that can be drawn. Therefore, this unit was considered appropriate for addressing the fifth aspect of NOSI, namely that inquiry procedures can influence results.

Second unit

The aim of the second unit was the explicit instruction of the CVS. The literature indicates that for the effective use of CVS, explicit teaching is required prior to its application by students (Lorch et al., 2010). In particular, it is important for students to be asked to distinguish between valid and invalid experiments and to justify the validity of appropriately designed experimental setups. Additionally, exposing students to invalid experiments has been shown to be especially effective (Schwichow et al., 2022). Awareness of common design errors that should be avoided during experimentation can support the development of students' metacognitive skills related to CVS and contribute to their conceptual understanding of the phenomenon under investigation (Schwichow et al., 2022).

In this context, the unit employed hypothetical scenarios through which students engaged in activities involving the identification of valid and invalid experiments, the interpretation of valid experimental designs, and the recognition of inconsistencies in invalid ones. This lesson also aimed to explicitly address the fifth aspect of NOSI, as it provided opportunities to discuss how the design of an experiment can affect the results it produces.

Third unit

The third unit focused on teaching the mechanism of heat transfer by conduction. A primary instructional goal was to confront students' alternative conception that heat has material properties, as this idea is considered an obstacle to the conceptual understanding of the phenomenon (Kesidou & Duit, 1993). In addition, the unit aimed to utilise CVS both for understanding the scientific content and for highlighting selected aspects of NOSI. The approach adopted for addressing these aspects was explicit and reflective. The teacher's reflective questions during the lesson, as well as during the concluding discussion, supported the scaffolding of students' thinking about NOSI. Table 3 presents the structure of the third unit.

As mentioned earlier, the design of this unit was based on the 5E instructional model. During the *Engage phase*, students were presented with a hypothetical scenario in which they were described as explorers encountering two adjacent locked doors inside an ancient structure. The doors were secured by a metal rod placed diagonally in front of them, with heat-sensitive locking mechanisms located at the upper and lower ends of the rod, each corresponding to one door. A heat source was positioned directly beneath the centre of the rod, and students were asked to predict whether heating the rod would result in the simultaneous unlocking of both doors or whether one door would unlock before the other, and to justify their reasoning. This scenario served to elicit students' alternative ideas and to identify the variables affecting heat transfer. Through engagement with the scenario, students were guided to formulate the research question: "*How does height difference from the heating source affect how quickly heat spreads above and below it?"* In this way, students recognised the direct relationship between the question posed and the inquiry procedures that would follow. At this stage, the third aspect of NOSI was highlighted, namely that inquiry procedures are guided by the question asked. During the *Explore phase*, students conducted experiments involving the heating of metals (Table 3) and recorded the data obtained. Subsequently, in the *Explain phase*, they were asked to interpret their experimental observations. At this stage, students answered the research question by relying on the data they had collected. Therefore, this phase was considered appropriate for addressing the seventh aspect of NOSI, according to which research conclusions must be consistent with the data collected. In the *Elaborate phase*, students were presented with a simulation illustrating the microscopic motion of particles in a solid during heating and were asked to explain their experimental observations using elements from the microscopic level. Finally, in the *Evaluate phase*, students' understanding of the scientific content was assessed through a relevant activity, and an overall reflective discussion was conducted using targeted questions aimed at highlighting and discussing the NOSI aspects addressed throughout the unit.

Table 3. Description of the 3rd unit of the TLS

Inquiry Practice (IP) & Aspect of NOSI	**Main expected learning outcomes** *(Students will:)*	**Main teaching activities** *(Activities:)*
IP: CVS NOSI3: Inquiry procedures are guided by the question asked NOSI5: Inquiry procedures can influence results NOSI7: Research conclusions must be consistent with the data collected	**Conceptual knowledge:** recognise that heat spreads at the same rate in all directions within metal rods, positioned with a slight inclination relative to the horizontal plane, regardless of the height difference from the heating point above and below **Procedural knowledge:** understanding aspects of CVS, e.g., the ability to distinguish between valid and invalid experiments **Epistemological knowledge:** recognising that every piece of research is linked and guided by a central research question, that inquiry procedures can influence results and that research conclusions must be consistent with the data collected	activities involving heating metal rods, positioned with a slight inclination relative to the horizontal plane and observing their marks, which bear a small amount of wax and have the same height difference from the heating point above and below (Valkanou et al., 2024a)

Note: NOSI3, NOSI5, and NOSI7 refer to the corresponding aspects of NOSI in Table 1.

Participants

The TLS was implemented in a fifth-grade class in a public primary school in Greece. The class consisted of 18 students (9 boys and 9 girls). During the implementation of the TLS, students worked in groups of three or four, across all phases of the instruction.

Data Collection And Analysis

Data were collected through multiple sources: (1) a written questionnaire consisting of seventeen tasks (seven targeting scientific content, three addressing the CVS, three focusing on modelling, and four addressing aspects of NOSI), which was administered before, during (after the fourth

unit), and after the implementation of the sequence; (2) video and audio recordings of all lessons; and (3) post-instruction group interviews conducted in focus groups.

In the present paper, the analysis focuses on the evaluation of students' understanding of (a) heat transfer by conduction in metals (conceptual knowledge), (b) the aspect of CVS reasoning related to distinguishing between valid and invalid experiments (procedural knowledge), and (c) the third aspect of NOSI namely that inquiry procedures are guided by the research question (epistemological knowledge), using data derived from a subset of the written questionnaire. Specifically, the evaluation of the aforementioned aspects of knowledge, presented in this study, was based on eight tasks, namely two tasks addressing scientific content, three tasks targeting the CVS, and three tasks focusing on aspects of NOSI.

The data obtained from the written questionnaire were analysed using a mixed-methods approach, combining qualitative and quantitative methods (Clark et al., 2021). Category construction was informed by a combined top-down and bottom-up analysis (Bryant & Charmaz, 2007). In the top-down analysis, students' answers were compared with the expected learning outcomes defined in the TLS, as well as with relevant categories reported in the literature. In parallel, a bottom-up analysis involved the iterative comparison of students' responses, allowing for the refinement of existing categories and the emergence of new ones. To enhance the trustworthiness of the analysis, two additional researchers independently categorised the responses, and discrepancies were discussed until agreement was achieved. Finally, descriptive statistics were used to quantify and summarise the categorised data.

Results

The results are presented in relation to the three learning areas addressed in the research question. The questionnaire comprised eight tasks assessing the knowledge aspects examined in this study. For reasons of brevity, this section reports indicative findings from three tasks of the written questionnaire, each corresponding to a different learning area (conceptual, procedural, and epistemological knowledge). The findings from the remaining tasks were consistent with those reported here; thus, the results reported are representative and sufficient to support the evaluation of the TLS aspects under investigation.

Task 1 investigated students' understanding of heat transfer by conduction in metals. Students were presented with a sketch depicting two identical metal rods, positioned with the same inclination relative to the horizontal plane. One rod was heated at its upper end, while the other was heated at its lower end. Students were asked to state and justify their views on whether they would feel heat when touching the end of each rod opposite to the heated one.

A representative scientifically accepted response (Category 3) was: *"In both cases, we would feel the same amount of heat, because in heat transfer by conduction, heat spreads equally in all directions"* (Table 4). Respectively, a representative response in Category 2 was: *"In both cases, we would feel heat, because heat goes everywhere",* in Category 1: *"I think we would feel more heat in B, because fire can go down more easily",* and in Category 0: *"No, because the rods are heated in the same way".*

As demonstrated in Table 4, a gradual shift in students' responses across the three tests is evident. In the Pre-test, the majority of responses were classified as alternative ideas, while no responses fell into the scientifically accepted or partially scientifically accepted categories. In the Middle-test, there was a substantial increase in the frequency of responses that were scientifically accepted or partially scientifically accepted. This was accompanied by a marked decrease in the frequency of alternative ideas. This trend continued in the Post-test, with a further increase in

scientifically accepted responses and the elimination of irrelevant or non-responsive answers. This pattern indicates an overall improvement in students' conceptual understanding.

Table 4. Students' answers at Task 1

Categories	Pre	Middle	Post
3: Scientifically accepted	-	5	6
2: Partially scientifically accepted	-	7	8
1: Alternative ideas	14	5	4
0: Irrelevant or No answer	4	1	-
TOTAL	18	18	18

Task 2 examined students' ability to identify a valid and appropriate experiment to investigate a specific scientific question. Students were provided with a table presenting four experiments (each consisting of two trials) investigating whether the colour of crayons affects their rate of melting. The first experiment was valid but not appropriate, as the only variable that changes is not the controlled variable. The second and third experiments were invalid, since although the controlled variable changes from one trial to the other, more than one variable is modified in each case. The fourth experiment was both valid and appropriate, as only one variable changes, namely the controlled variable. Students were asked to select and justify which experiment would lead to a sound conclusion.

A representative scientifically accepted response (Category 3) was: *"The fourth experiment, because only the colour changes. In the others, either more than one thing changes or the colour does not change"* (Table 5). Respectively, a representative response in Category 2 was: *"I believe that experiment 4 would lead to a safe conclusion, because in experiment 4 only one variable changes and the steps of the CVS method are followed correctly",* in Category 1: *"Experiment 3, because it has different colour, size, and time"*, and in Category 0: *"Yes, with a different colour it will be better".*

As demonstrated in Table 5, a gradual shift in students' responses is evident across the three tests. Initially, in the Pre-test, no student provided a correct description of the CVS, while most responses were partially correct or incorrect. In the Middle-test, there was a substantial increase in the frequency of correct responses, accompanied by a decrease in incorrect responses. This improvement was sustained in the Post-test, with the number of accurate responses remaining consistent and a further decline in incorrect descriptions. The distribution of responses indicates a gradual improvement in students' understanding of the CVS.

Table 5. Students' answers at Task 2

Categories	Pre	Middle	Post
3: Correct description of CVS strategy	-	5	5
2: Partially correct description of CVS strategy	7	4	7
1: Incorrect description of CVS strategy	10	8	6
0: Irrelevant or No answer	1	1	-
TOTAL	18	18	18

Task 3 examined students' understanding of the third aspect of NOSI, namely: *"Inquiry procedures are guided by the question asked".* Students were presented with a scenario involving two groups of scientists who were investigating whether certain tyre brands are more prone to damage. The first group tested multiple tyre brands on the same type of road, whereas the second

group tested a single brand on different types of roads. Students were asked to explain why the procedures followed by one of the two groups were better than those followed by the other.

A representative scientifically accepted response (Category 3) was: *"I agree with Group A, because the question is whether some tyre brands can burst more easily than others, so there must be many tyre brands"* (Table 6). Respectively, a representative response in Category 2 was: *"Group A followed the correct steps, because it used many tyre brands",* in Category 1: *"Group B followed the steps better, because there are many types of roads and a tyre has to withstand all of them",* and in Category 0: *"The steps followed by Group A were better".*

As demonstrated in Table 6, a progressive shift in students' responses was observed across the three tests. In the Pre-test, the majority of responses were classified as either mixed or naïve views, with only a small number reflecting informed views. In the Middle-test, there was an increase in the frequency of informed views, accompanied by a reduction in naïve and irrelevant responses. This tendency became more evident in the Post-test, with informed responses demonstrating a substantial increase and naïve or irrelevant answers being eliminated, thus indicating an overall enhancement in students' comprehension of the examined aspect of NOSI.

Table 6. Students' answers at Task 3

Categories	Pre	Middle	Post
3: Informed views	2	4	8
2: Mixed views	8	10	10
1: Naïve views	5	2	-
0: Irrelevant or No answer	3	2	-
TOTAL	18	18	18

Discussion And Conclusions

The present study investigated the extent to which students' understanding of (a) heat transfer by conduction in metals (conceptual knowledge), (b) the aspect of CVS reasoning related to distinguishing between valid and invalid experiments (procedural knowledge), and (c) the third aspect of NOSI namely that inquiry procedures are guided by the research question (epistemological knowledge), improved following the TLS implementation.

Overall, the results suggest a modest positive improvement in understanding across the three aspects of knowledge addressed in this paper. Regarding conceptual knowledge, students demonstrated a progressively more scientifically consistent understanding of heat conduction. In particular, they gradually moved away from viewing heat as a material substance within the context of heat conduction phenomena, and provided interpretations aligned with the scientific view. The observation that, during the heating of metal objects, heat propagates at the same rate in all directions, regardless of the vertical distance from the heating point (above and below it), appeared to have strong instructional value. This observation helped students distance themselves from their initial material conception of heat, in line with findings from a previous implementation of the experimental activities employed in the present TLS (Valkanou et al., 2024b). Moreover, students' understanding of heat conduction in metals further improved following their engagement with subsequent units explicitly addressing the other two modes of heat transfer (convection and radiation). This finding reinforces the need to teach the three modes of heat transfer as conceptually distinct, as documented in the literature (Çoruhlu, 2017). It suggests that such an instructional approach not only enhances students' understanding of each mode but also contributes to the remediation of the alternative idea of heat as a material entity, which constitutes a major obstacle to the conceptualisation of heat transfer (Kesidou & Duit, 1993). With respect to procedural knowledge, the findings show an improvement in students'

understanding of aspects of the CVS, especially in identifying valid experimental designs and justifying their choices. Although some students continued to exhibit partial or mixed understandings, the overall trend seems to be consistent with the literature, which indicates that explicit instruction combined with exposure to both valid and invalid experiments contributed to the development of more informed procedural reasoning (Schwichow et al., 2022). Concerning epistemological knowledge, students showed notable progress in their understanding of the idea that inquiry procedures are guided by the research question. The increase in informed responses suggests that the explicit and reflective approach adopted in the TLS, supported by targeted teacher questioning and whole-class discussion, was effective in fostering students' epistemological understanding, as also reported in the literature (Witucki et al., 2023). Taken together, these findings are consistent with the arguments presented in the introduction, namely that the integration of inquiry practices with explicit and reflective instruction can support students' understanding of both scientific content and aspects of NOSI (Bächtold, 2024).

In the next phase of the research, further statistical analysis of the data would be valuable to explore potential correlations between conceptual, procedural and epistemological knowledge, thus providing deeper insights into the relationships between these learning areas within the TLS framework. In addition, following these analytical procedures, it would be meaningful to refine and further improve the TLS based on the identified findings and to re-implement it, in order to further examine its effectiveness.

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"We Had A Lot Of Freedom." Learning Of Students With High Diversity In An Open Inquiry "Lernwerkstatt" Setting

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According to the OECD learning compass, effective learning environments are needed to foster student agency. Inquiry-based learning which is increasingly present in Austrian curricula for primary and lower secondary school has the potential to foster student agency. Unfortunately, it is still only partially present in school lessons, the asking of scientifically answerable questions is particularly underrepresented. Lernwerkstatt, which could be translated into learning workshop, is an open inquiry learning format for students where they can ask their own questions, which are stimulated by learning landscapes. In a learning landscape the students find different objects, pictures, tools or other things, which spark their interests and trigger a research question. After finding their question the students have time to develop a research design and finally answer the question. The students are responsible for the whole inquiry and are closely scaffolded throughout the process. The research project "Learning-researching – Lernwerkstatt along different diversity dimensions" follows two primary and two lower secondary school classes. The research diaries of the students were collected and analysed via qualitative content analysis. After the Lernwerkstatt a students' questionnaire concerning the learning format and the perceived scaffolding were conducted. In this paper a Lernwerkstatt regarding the topic "Habitats and environments" is introduced, the students' research questions and their perceptions of the learning format is presented.

Keywords: Inquiry-Based Learning, Learning Environments, Qualitative Research

Introduction

According to the OECD learning compass student agency should be fostered by effective learning environments. There, students have the possibility to decide what and how they want to learn in order to achieve the long-term goal of "learning how to learn" (OECD, 2019, p. 33). Inquiry-based learning is a way to foster scientific thinking, which leads to scientific literate students (AAAS, 2012). Lernwerkstatt (Puddu et al., 2012) which possibly could be translated into learning workshop is an open inquiry-based learning format (Blanchard et al., 2010) where the students are responsible for the whole inquiry process. At level three of the levels of inquiry (see Table 1) they pose a question, decide which inquiry method is suitable for the research, and finally they answer their own research question.

Table 1. Levels of Inquiry (Blanchard et al., 2010, p. 581)

	Source of the Question	Data collection Methods	Interpretation of Results
Level 0: Verification	Given by teacher	Given by teacher	Given by teacher
Level 1: Structured	Given by teacher	Given by teacher	Open to student
Level 2: Guided	Given by teacher	Open to student	Open to student
Level 3: Open	**Open to student**	**Open to student**	**Open to student**

As learning workshop is not considered an adequate translation, the term Lernwerkstatt is used further. The Lernwerkstatt at the University College of Teacher Education Vienna is a room, which is nicely furnished and contains many interesting objects, books, materials for experimentation and consumables (Ovrutcki et al., 2024; Puddu & Ovrutcki, 2025). Additionally,

a learning landscape on a special topic is created. The learning landscape within this research project is about habitats and environments, so the students find many objects, books and models matching the topic like models of animals living in the rainforest, a globe, a model of diverse students where one is using a wheelchair, minerals and garbage cans.

Lernwerkstatt as an open inquiry-based learning format is inherently inclusive. Every learner can pose their own questions and do their own research according to their interests, competencies and skills.

A very important part of inquiry-based learning is the scaffolding (Hofer, 2020). The students need to learn, for example, how to frame a question, how to gather and handle data, how to use available information either in books or on websites. Scaffolding of the language is also necessary, on the one hand because of technical terms, and on the other because the language of instruction is often not the first language of the students (Gabler et al., 2020). The individual scaffolding, as is done in the Lernwerkstatt, meets the needs of the students.

Procedure Of A Lernwerkstatt

In the Lernwerkstatt, the students have three mornings to do research. On the first day, the rules for working in the Lernwerkstatt and possible research methods are discussed, which include e.g. interviews, observations, research from books and encyclopaedias, but also experiments. After that the students discover the topic of the Lernwerkstatt through a puzzle, through pictures that are put together or through colouring dictations. There are many ways to get started here, but it is important that the introduction already arouses curiosity about the topic. After this initial introduction, they visit the learning landscape to find interesting things and subsequently create research questions. The first walk through the learning landscape is first and foremost for making observations, which they can already note down in the research diary they received earlier. The observations are then discussed and the second walk through the learning landscape follows. Initial questions are noted in small pieces of paper. Students with similar research questions can work together and form a group. Then the research begins. At the end of the first morning the teachers and the students meet in a seating circle and discuss the progress of the research and if additional materials or information are needed which can be organized in the afternoon. On the second morning the research process can be continued. The third morning is dedicated to the presentation of the research process and the results.

Research Design

In the research project “Learning – researching. Lernwerkstatt along the diversity dimensions”, a design based research study (Obczovsky et al., 2024), which started in 2024, lies the focus on learning with very diverse students. The main goal is to establish Lernwerkstatt in the affiliated inclusive schools and to encourage teachers to implement inquiry-based learning in their classrooms. To achieve this goal, we wanted to generate enthusiasm among the teachers. Four urban school classes, two primary school classes (grade 4) and two secondary school classes (a multi-grade class with the grades 5 to 8 and a class with grade 5), a total of 89 students, attended Lernwerkstatt between September 2024 and June 2025. The students in these classes show a high diversity. Many children have a first language other than the language of instruction, some have refugee experience or disabilities.

In the case of the middle school classes, the teachers were part of the project and supported the data collection. They were also involved in the scaffolding. In the first class (middle school, multi-grade class) the teacher recruited teacher students for additional scaffolding.

In the case of primary school, teacher students came with their class they practiced in. The teachers of the class accompanied the teacher students and took over groups to scaffold. Sometimes assistant teachers additionally supported the scaffolding.

The research questions are: “What questions do students frame within the topic of habitats and environments?” How do students with high diversity perceive open inquiry-based learning format Lernwerkstatt? How do the students assess their own research? The answers to the research questions provide information for the further development process.

The students write or draw in their research diary during their inquiry. Guiding questions and scaffolding helps the students to write down their questions, what they need for their research, what methods they use and the answer they find to their questions. Additionally, they describe their presentations of the findings to the class. The research diaries were analysed via qualitative content analysis (Kuckartz & Rädiker, 2022).

For the second and the third research question concerning the perception of the open inquiry-based learning format Lernwerkstatt a questionnaire was used with closed items like “I felt comfortable in the Lernwerkstatt” “I am satisfied with my work in the Lernwerkstatt” or “The teacher was there when I needed something” The response scale had four levels, + +, +, - and - - (see Table 1).

At the end of the questionnaire, we posed four open questions about what the students like best and least, what they could do differently the next time and what else they like to say about Lernwerkstatt.

Of the 89 students who attended the Lernwerkstatt 82 students competed the questionnaire.

The closed items of the questionnaire were analysed using descriptive statistics. Therefore, the mean value and standard deviation were calculated. For the calculation the scale was converted, the highest value was four (++), the lowest value was one (--). The open items were analysed using qualitative content analysis (Kuckartz & Rädiker, 2022).

Additionally we took field notes (Thierbach & Petschick, 2022) to document our observations and enrich the analysis.

Findings And Conclusions

The data of this paper stems from four school classes. Two primary school classes (grade 4) with 18 and 17 students respectively and two middle school classes, one multi-grade class with 30 students and one 5th grade class with 24 students visited the Lernwerkstatt.

The students frame very different questions. The questions of the 5th to 8th grade ranged from “How many underground stations are there?” to “How many art styles are there and how do they look like?” Some students asked about specific countries or cities, their structure and how people live there. Other questions were about the difference of the water in a pond, lake and sea. The primary school students asked about the first instrument, about pharaohs, Europe, planets or crystals. So, while the questions are not very different, the research process differs according to the grade and the skills.

In answer to the research questions “How do students with high diversity perceive open inquiry-based learning format Lernwerkstatt? How do the students assess their own research?” the analysis of the questionnaire (see Table 2) showed that the students felt quite comfortable in the Lernwerkstatt ($\bar{x}$=3.390) and were satisfied with their work ($\bar{x}$=3.439) The students also recognized the scaffolding. The item “The teacher was there when I needed something” showed a mean value of 3.622. The item “I learned a lot in the Lernwerkstatt” showed a mean value of

3.463. There may be various reasons for this result. One possible explanation is that the students learn more implicitly, or they don't recognize the learning because the students choose the content.

Table 2. Evaluation of the Lernwerkstatt (n=82).

	Mean value [$\bar{x}$]	Standard deviation [σ]
I felt very comfortable in the Lernwerkstatt	3.390	0,676
I am very satisfied with my work in the Lernwerkstatt	3,439	0,717
I was able to work on the questions that interest me	3,476	0,784
The teacher is interested in my opinion	3,317	0,714
The teacher was there when I needed something	3,622	0,618
I learned a lot in the Lernwerkstatt	3,463	0,752
I made an effort to document accurately	3,439	0,627
I was very satisfied with my/our presentation	3,451	0,751
I liked the other presentations very much	3,512	0,703

The responses of the students to the open-ended question "The best of Lernwerkstatt was…" were analysed via qualitative content analysis using inductive categories. Four categories were found as shown in Table 3. In response to this open question about what the students liked best, the most common category in the winter term was "student agency" with 19 out of 42 answers. It was important for the students to be allowed to choose, to choose the topic, to choose the people they learn with, to have the freedom to experiment. The Lernwerkstatt therefore fulfills the OECD's requirement to offer learning environments that promote student agency. The second most common response is related to elements of the work in a Lernwerkstatt like the learning environment, the learning landscape or the presentation at the end of the Lernwerkstatt. The category 'scaffolding' was only mentioned once, the category "mentioning of specific objects" was found six times when the students wrote how proud they were of the models built by them.

Table 3. Mentionings of students in open question: "What did you like best?"

	Winter term		Summer term		
Categories/classes	1 (middle school, multi-grade, n=30)	2 (primary school, 4th grade, n=18)	3 (middle school, 5th grade, n=24)	4 (primary school, 4th grade, n=17)	Sum
Student agency	10	9	2	3	24
Elements of "Lernwerkstatt"	11	5	10	10	36
Scaffolding	1	0	1	0	2
Mentioning of specific objects made	3	3	1	2	9

The summer term was different. There were only five answers categorized as "student agency" and 20 answers as "elements of Lernwerkstatt". The answers in the categories "scaffolding" and "mentioning of specific objects made" were comparable to the winter term as there were less students in the classroom. To get to the bottom of the difference, field notes, which we wrote down to reflect the days of Lernwerkstatt, were analysed. There we found a few clues. The third class, which was a 5th grade middle school class, was used to work on projects and on their own

questions. Even if the system and the surroundings were different, the type of learning was familiar. That is why we assume that they regarded independence as a matter of course and therefore did not specifically mention it in the open question. The fourth class we analysed, a 4th grade primary school class, was different. The teachers of the class, who did the scaffolding, visited the Lernwerkstatt for the first time and had so much fun, maybe too much fun, that they took over the inquiry for some groups. They led instead of supporting the groups. Therefore, the students still enjoyed learning but were missing out on the Lernwerkstatt experience, which is shown in the answers where we categorized ten answers in “elements of Lernwerkstatt” category and only three in “student agency”.

The most criticized aspect (What did you like least?) was the insufficient number of breaks. This way of learning is strenuous, so it is important to implement more breaks than usual in a school day.

The last question was about what else they want to say about Lernwerkstatt. The students wrote that they liked Lernwerkstatt, said thank you to the heads of Lernwerkstatt, and that they would like to repeat the experience.

Discussion

For teachers, Lernwerkstatt means having confidence in the students' abilities and opening up the space for open inquiry-based learning. This freedom in learning, which is demanded on the one hand by the OECD in the learning compass and on the other hand by the students themselves, is made possible in the Lernwerkstatt. But there are pitfalls.

Because we worked in real classroom situations, the authors had to deal with varying teachers and sick leaves. So, we didn’t always know who would provide scaffolding for the class in addition to the authors who led the Lernwerkstatt. These circumstances led to the situation that we couldn’t convey the challenges of scaffolding and open inquiry-based learning to the teachers in a meaningful way.

Based on the small sample, we would like to make few suggestions. Teachers should be familiar with open inquiry-based learning and ideally have experience in research which aligns with the literature (Capps & Crawford, 2013). Teachers should be familiar with scaffolding of students. As a consequence, the authors plan to offer a Lernwerkstatt for teachers to experience the learning process for themselves beforehand. There we can make the inquiry process and the nature of science explicit and reflect so they feel equipped to work with their students accordingly.

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Artificial Intelligence In Experimentation: A Bibliometric Approach

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This study explores the integration of Artificial Intelligence (AI) in experimentation within science education through a bibliometric lens. Although AI has gained increasing traction in educational research, its role in supporting or transforming experimental science learning has received limited attention. Using data from 2,455 publications indexed in Scopus, this study investigates three key areas: the evolution of publication rates over time; the most active disciplines, countries, and institutions; and the emerging thematic clusters. Descriptive statistics and keyword co-occurrence mapping via VOSviewer were used to analyse publication trends and research directions. Findings indicate a sharp increase in relevant publications after 2020, with notable contributions from computer science and engineering, as well as from institutions in China, the United States, and Europe. Seven thematic clusters were identified, reflecting diverse interests across pedagogy, AI techniques, infrastructure, cognitive processes, and interdisciplinary applications. The study underscores a growing intersection between AI and inquiry-based experimental teaching, highlighting opportunities for cognitive development, teacher support, and accessibility. It also reveals gaps in pedagogical integration and equity of access. These findings offer valuable insights for educators, policymakers, and edtech developers seeking to integrate AI meaningfully into science experimentation.

Keywords: Artificial Intelligence, experimentation, bibliometrics

Introduction

The integration of Artificial Intelligence (AI) into education is reforming teaching and learning institutions worldwide. This transformation is primarily driven by AI's innovative capabilities, including personalized feedback, intelligent tutoring systems, learning analytics, and curriculum adaptation. In science education, which relies on inquiry, problem-solving, and experimentation, AI can promote student engagement with complex phenomena through modeling, testing, and sense-making (Akhmadieva et al., 2023; Almasri, 2024; Dai, 2023; Park et al., 2023). Specifically, experimentation—a core element of science teaching involving hypothesis formulation, data collection, and variable manipulation for knowledge construction—can benefit from AI in several ways. Virtual labs, simulations, adaptive systems, and data processing tools can help teachers overcome barriers such as equipment shortages, safety issues, and time constraints (Cheung et al., 2024; Paul et al., 2016; Tang et al., 2024).

Despite the expanding use of AI in science instruction, a limited number of studies focus specifically on its role in experimentation. These studies suggest that AI serves not only as a tool for effective experimentation but also as a force that transforms cognitive and pedagogical aspects, such as metacognition and scientific thinking (OECD, 2024; Ng et al., 2024). A bibliometric study can reinforce these findings by offering insights into research trends, key contributors, and emerging themes in the literature. This study aims to provide significant outcomes regarding the evolving relationship between AI and experimentation in science teaching, which can be useful for educators, policymakers, and education experts (Akhmadieva et al., 2023; Donthu et al., 2021; Marzi et al., 2024; Öztürk et al., 2024).

Literature Review

Experimentation In Science Teaching

Scientific experiments offer students opportunities to observe scientific phenomena as they unfold in real time, rather than merely reading about them or watching demonstrations. This direct engagement bridges the gap between abstract theoretical concepts and tangible experiences, enhancing conceptual understanding, curiosity, and retention. When learners witness cause-and-effect relationships, such as chemical reactions, forces in motion, or energy transfers, they are more likely to internalize key scientific ideas (Lee et al., 2023; Paul et al., 2016).

Experimentation is, therefore, fundamental to teaching science. It is a systematic process of investigating scientific questions that involves hypothesizing, observation, data collection, and analysis. It plays a multidimensional role by fostering scientific literacy. Through experimentation, learners can control variables such as mass, volume, light, temperature, voltage, and distance, allowing them to witness how concepts relate to one another. Learners can then participate in evidence-based explanations, exchange ideas, and engage in argumentation. This process enables them to actively construct knowledge within inquiry-based learning activities (Paul et al., 2016; Tang et al., 2024). Learners develop skills such as reasoning, critical thinking, scientific thinking, modeling, and metacognition, which lead to cognitive development, a better understanding of scientific content, and an appreciation of the nature of science and epistemic practices. Hence, national curricula and frameworks present experimentation as a core practice in science teaching (Lee et al., 2023; OECD, 2024).

There is considerable interest in the role and influence of information and communication technologies, such as AI, in experimentation. This integration can streamline the process, offering several advantages and disadvantages (Tang et al., 2024).

AI In Science Teaching:

The use of AI in science teaching presents both opportunities and challenges. On one hand, AI can enhance instruction through intelligent tutoring systems, adaptive learning tools, virtual laboratories, and generative applications, leading to more effective lesson plan design and improved learning outcomes (Ng et al., 2024; Ivanova et al., 2024). For example, with AI, teachers can quickly adapt session content and pace to meet individual learners' needs, providing timely feedback and fostering critical thinking (Almasri, 2024; Park et al., 2023). Moreover, applications such as virtual labs provide avenues for experimentation, especially in scenarios that are dangerous, complex, or inaccessible in traditional classroom settings (Tang et al., 2024; Park et al., 2023). Simultaneously, inquiry-based learning, a dominant teaching approach in contemporary literature, can be supported by AI, as it can enhance hypothesizing, experimental design, scientific thinking, collaboration, cooperation, creativity, and other fundamental components of inquiry (Lee et al., 2023).

AI is also associated with cross-curricular teaching subjects such as Science, Technology, Engineering, Arts, and Mathematics (STEAM), which are linked to contemporary science teaching paradigms. It can facilitate feedback and data collection from activities such as inquiry-oriented tasks and experiments, aiding analysis, decision-making, and knowledge construction (Cheung et al., 2024; Darayseh, 2023). Furthermore, teachers can use AI to monitor learners' progress and performance development, identify barriers, and map innovative learning paths (Ng et al., 2024; Ivanova et al., 2024). Through these interactive and adaptive features, AI can foster

stronger motivation among learners to actively participate in science sessions and develop a positive attitude toward the subjects and inquiry (Almasri, 2024; Park et al., 2023).

On the other hand, challenges arise with the use of AI. A major concern is linked to ethical, epistemological, and pedagogical issues, primarily due to data validity, privacy, algorithm accuracy, and overdependence on technology, which can assist but also undermine scientific thinking and other essential skills (Tang et al., 2024). Additionally, effective AI integration requires professional development and competencies from educators, who may not always feel confident or prepared to integrate these technologies into their work (Genc & Kocak, 2024; Cooper, 2023).

This challenge is compounded by the need for AI to align with curricula, syllabi, lesson plans, and education policies. In other words, attention must be paid to how AI is used in science teaching to ensure effective learning outcomes and to identify or develop AI tools that are compatible with teaching processes and contexts (Lee et al., 2023; Ivanova et al., 2024). Finally, inequalities in AI usage among countries and regions persist, as technologically advanced countries are more familiar with AI and the development of appropriate policies, which cannot be easily implemented in less advanced regions (Dai, 2023; Akhmadieva et al., 2023).

Bibliometric Analysis Of Trends Regarding AI In Science Teaching

Several bibliometric studies have examined the integration of AI into science teaching. These studies report a growing rate of relevant publications, with notable acceleration after 2020. This aligns with the general trend in digitalization and its impact on educational settings. A global interest exists around this topic, as publications originate from many countries, although the greatest number comes from the United States, China, and several European countries such as the United Kingdom, Germany, and Spain (Jia et al., 2023). The most prolific authors or researchers publishing in this area come from technical fields, such as computer science, with a limited number from education studies or social sciences. Consequently, emphasis is placed on engineering, computer-oriented issues, and content delivery, while less attention is given to pedagogical and education-oriented issues, such as experimentation in science teaching or inquiry-based instruction (Genc & Kocak, 2024; Ng et al., 2023). Correspondingly, the clusters drawn from these studies focus on topics such as educational robotics, STEAM, automation, prediction, ethical issues, and personalized learning and adaptivity. The number of studies examining pedagogical matters or teaching practices remains limited (Jia et al., 2023; Genc & Kocak, 2024).

Intersections Between AI And Experimentation

When it comes to the integration of AI in experimentation, as with science teaching in general, potential advantages and disadvantages can emerge. On one hand, AI can assist in planning experimental activities and learning scenarios that incorporate them. Thanks to AI-based virtual laboratories, it is possible for a session to include experimental activities that would otherwise be unfeasible due to safety, cost, or equipment shortages. Such simulations and virtual labs can also aid learners in tasks of hypothesizing, variable control, data collection, and analysis. This support fosters positive attitudes toward experimentation along with inquiry-based learning (Cheung et al., 2024; Cooper, 2023; Ivanova et al., 2024; Lee et al., 2023).

However, the use of AI in experimentation may oversimplify tasks and limit students' engagement in processes such as using materials, handling sensors, and measuring, which are basic components of experimentation. It may also deter them from learning other essential characteristics, such as argumentation, trial-and-error, and dealing with ambiguous data. Additionally, processes such as auto-grading and auto-generated outputs may undermine

learners' ability to judge, draw conclusions, and actively construct knowledge (Almasri, 2024; Paul et al., 2016; Tang et al., 2024).

In short, integrating AI into experimental tasks in science sessions can facilitate inquiry-based learning and familiarity with experiments through actions that ease their implementation. However, this approach can also impede the development of experimentation and inquiry skills and competencies that learners are expected to acquire. Teachers and education policymakers must thus be prepared to promote the appropriate use of AI in experimentation (Almasri, 2024; Darayseh, 2023).

Methodology

An examination of contemporary research trends regarding the intersection between AI and science teaching reveals a growing interest and recognition of AI's potential (Jia et al., 2023; Ng et al., 2024). However, there is a shortage of studies examining trends at the intersection of AI and experimentation in science teaching. A more focused bibliometric study is needed to outline the basic findings of research productivity around this topic and point out disciplinary and conceptual emphases (Genc & Kocak, 2024; Tang et al., 2024).

This study aims to address this gap with a bibliometric approach, which can unveil the desired trends by providing insights into publication rates, authors' research areas, regions, countries, affiliations with the most contributions, and thematic clusters. The research questions are formulated as follows:

- What are the publication rates for integrating AI and experimentation in science teaching?
- Which disciplines, countries, and institutions are most active in this area?
- What key topics and thematic clusters are identified in the research? (Donthu et al., 2021; Marzi et al., 2024; Öztürk et al., 2024)

The Scopus database was selected as the most appropriate data collection tool for such a study because it can gather publications, such as articles, books, or papers, around a specific topic. This is accomplished by executing a search query composed of terms relevant to this topic or its subthemes. Apart from gathering data, it provides functions that assist in analysing these publications concerning the three research questions. (Scopus, 2025).

A search was conducted on Scopus by executing the following command:

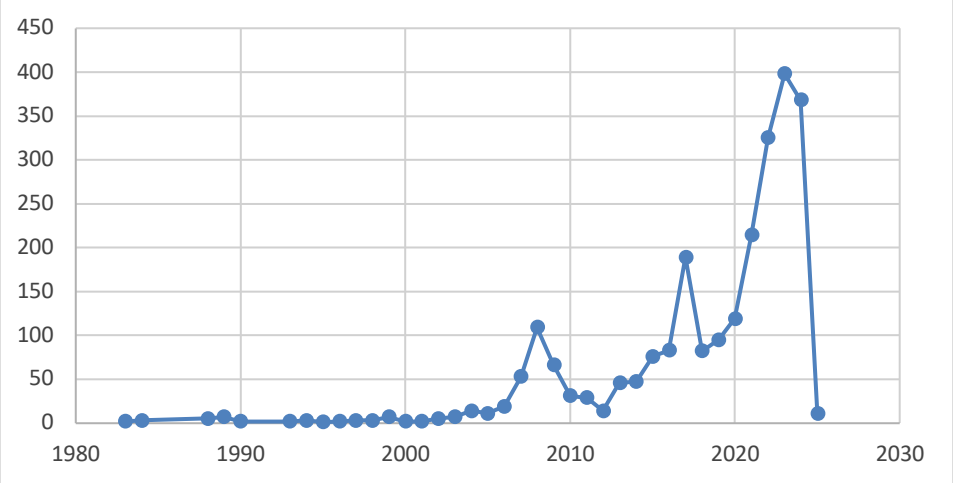
TITLE-ABS-KEY (experimentation OR experiment OR science AND education AND experiments) AND TITLE-ABS-KEY (artificial AND intelligence)

The search returned 2,453 publications. The data needed to answer the first two questions were obtained through the relevant analysis functions provided by the Scopus platform. The data were gathered and downloaded in sets of Microsoft Excel files that included the number of publications per year, along with research areas, countries, regions, and affiliations of the most authors or contributors. These data were analysed using descriptive statistics. To address the third research question specifically, the keyword co-occurrences of publications were gathered through Scopus, but the clusters were designed and visualized with VOSviewer, which assists in precisely identifying clusters of publications that can clearly reflect research trends and patterns. The analysis, therefore, included a combination of quantitative bibliometric mapping and qualitative cluster interpretation. This approach provides a clear and comprehensive picture of research, examining the role of AI in experimentation in science teaching. This is a common approach in bibliometric studies (Donthu et al., 2021; Scopus, 2025; Van Eck & Waltman, 2010).

Findings

Regarding the first research question about publication rates per year, the findings reveal that the earliest publications can be traced back to 1983. This indicates a long-standing interest, although initially limited, as several years had only five or seven publications, and in 1995, there was only one. This volatility persisted until the 2010s, with specific years, such as 2008 and 2017, showing significantly more publications than the preceding or following years. Nevertheless, a remarkable acceleration was noticeable after 2020, when the number of publications exceeded one hundred, and in 2023 and 2024, it even reached three hundred (Scopus, 2025).

Figure 1. Publications per year (Scopus, 2025).



Regarding the second research question, most authors who publish on this topic work in computer science, accounting for a large portion of the publications. Other contributing science-oriented disciplines include engineering, mathematics, physics and astronomy, and materials sciences. Several publications also come from social sciences and health areas, as shown in Figure 2. The countries with the most contributions include China and the United States, followed by the United Kingdom, Germany, Spain, Japan, Canada, Taiwan, India, Australia, and South Korea, as illustrated in Figure 3. Finally, the affiliations with the most contributions include the Chinese Academy of Sciences as the most prolific single institution, followed by the Ministry of Education of China and Carnegie Mellon University. Other notable institutions include Tsinghua University, Stanford University, and MIT, suggesting a strong emphasis on AI tool development over experimentation in science pedagogy from universities and governmental bodies (Jia et al., 2023; Genc & Kocak, 2024).

Finally, regarding the third research question, keyword analysis led to the identification of seven thematic clusters using VOSviewer software, as displayed in Figure 4. The first cluster, which is the largest, focuses on pedagogy and contains keywords such as teaching practices, learning, achievement, professional development, engagement, and science instruction. The second cluster pertains to AI techniques and includes keywords such as deep learning, machine learning, chatbots, and intelligent systems. The third cluster centres on human-centred learning and contains keywords such as motivation, attitudes, satisfaction, creativity, and learning preferences. The fourth cluster focuses on data analytics and modelling, containing keywords such as prediction, classification, data mining, and decision-making. The fifth cluster addresses technological infrastructure and includes keywords such as flipped classroom, e-learning, mobile learning, simulations, and digital platforms. The sixth cluster pertains to cognitive aspects and includes keywords such as cognitive load, metacognition, conceptual understanding, and problem-solving. The seventh cluster addresses cross-disciplinary applications and contains keywords such as interdisciplinary, health sciences, and engineering labs. Each cluster reflects a

conceptual domain in the integration of AI and experimentation in science teaching (Almasri, 2024; Darayseh, 2023; Van Eck & Waltman, 2025).

Figure 2. Subject areas (Scopus, 2025).

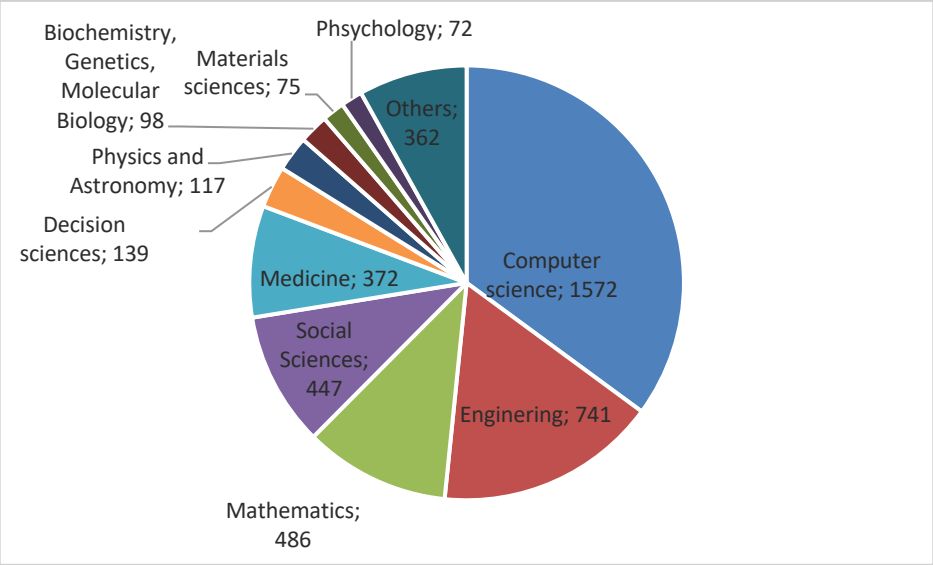


Figure 3. Countries with the most contributions (Scopus, 2025).

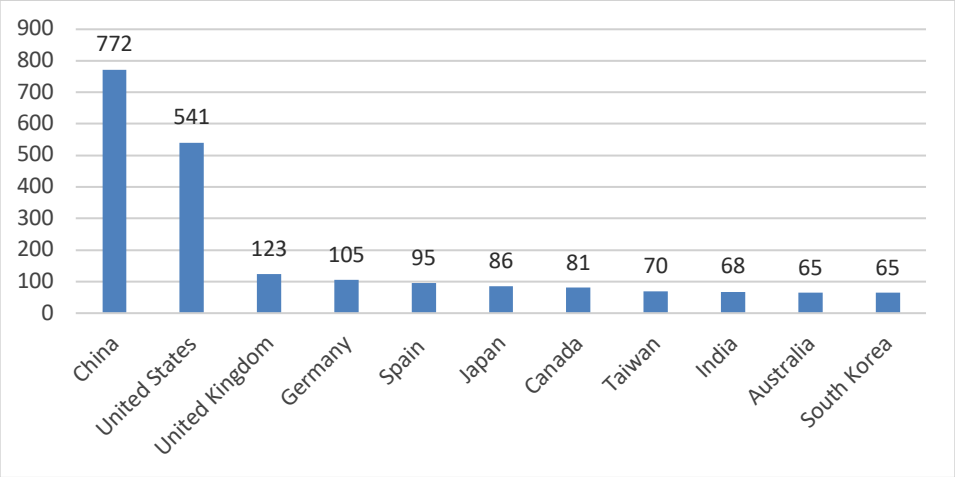
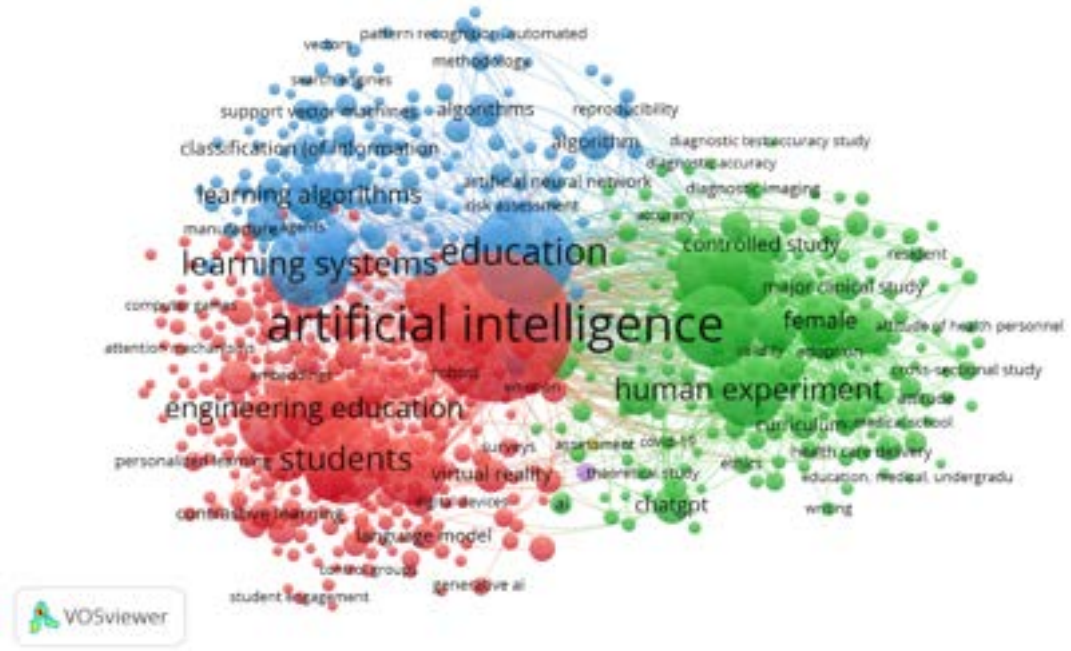


Figure 4. Clusters (Van Eck & Waltman, 2025).



Discussion

An analysis of the rate of publications per year indicates a sustained and growing interest in the role of AI in experimental science teaching over the last few decades. The non-linear growth pattern, with periods of declining publications, especially until the mid-2010s, is typical of fields undergoing conceptual formation (Donthu et al., 2021). This fluctuation can be explained by early pilot implementations of AI, without a specific focus. This changed drastically after 2018 and was not disrupted by challenging periods such as the COVID-19 pandemic, likely due to the significant development of AI tools (Marzi et al., 2024; Öztürk et al., 2024), which were subsequently introduced into educational practices and settings (Jia et al., 2023; Ng et al., 2024).

Although the publication rates appear to taper slightly after 2023, indicating a possible saturation of the field, the number of publications remains high, indicating a vibrant area of research (Donthu et al., 2021). This may be related to interest in technological advances such as virtual labs or AI-oriented learning platforms, which provide opportunities for teaching innovation, especially in experiments and inquiry-based approaches. Moreover, it may reflect educational researchers' interest in topics such as ethics and critical pedagogy (Genc & Kocak, 2024; Ng et al., 2023; Paul et al., 2016; Tang et al., 2024).

Regarding the second research question, the dominance of computer science publications reinforces the notion that technological advances drive innovation and research. The parallel presence of publications from social sciences suggests an interest in the implementation and use of AI in experiment-driven science instruction, either as a tool for experimental teaching activities or as a means to reshape students' attitudes toward science, scientific knowledge, and inquiry (Akhmadieva et al., 2023; Almasri, 2024; Genc & Kocak, 2024).

The strong presence of universities and governmental institutions in publications from various countries indicates a global interest, which may reveal funding and infrastructure in institutions to support AI use in experimental science teaching. However, the predominance of publications from technological disciplines raises concerns about the focus of research on social aspects such as pedagogy and ethical issues, although these areas are not entirely neglected. Additionally, the concentration of publications in specific countries, particularly English-speaking ones, may highlight inequalities in interest and access to AI tools for pedagogical purposes. Despite these concerns, evidence exists regarding cross-disciplinary and international collaborations between AI experts and education specialists (Almasri, 2024; Park et al., 2023). This reflects a recognition of AI's potential in experimental science teaching (Ng et al., 2024; Ivanova et al., 2024).

As for the third research question, the prominence of pedagogy can be associated with interest in dominant paradigms of experiment-oriented science teaching, such as learner-centered and inquiry-based approaches. This, combined with the clusters that emphasize AI techniques and human-centered learning, aligns with general findings that AI is reshaping pedagogy and can be associated with instructional methods that respond to learners' experiences and needs, particularly those that utilize experiments. The emphasis on professional development and learning effectiveness underscores the importance of teacher preparation (Akhmadieva et al., 2023; Almasri, 2024; Dai, 2023; Park et al., 2023).

The clusters focusing on technological infrastructure and functions, such as analytics, can be associated with AI's potential for promoting instruction where experiment implementation, based on context-rich learning experiences, is combined with virtual labs, simulations, or other practices that enhance digital awareness, feedback innovation, assessment, and knowledge construction within STEAM-oriented activities. This further justifies that AI can enhance experimentation by facilitating the execution of related activities in real-time and beyond classroom constraints (Park

et al., 2023; Zhang, 2021). The final clusters prove that cognitive scaffolding can be achieved through the use of AI in experiments, as it can assist not only in their execution but also in the development of scientific skills, such as hypothesizing, reasoning, metacognition, and problem-solving. As implied by the clusters, this can be applied in cross-disciplinary contexts, such as health sciences, robotics, and environmental projects. In fact, these clusters also provide evidence that AI can be utilized in designing experimental activities in such subjects or topics, leading to improved learning outcomes (Cheung et al., 2024; Ng et al., 2024; Paul et al., 2016; Park et al., 2023; Tang et al., 2024).

Conclusions

This study concludes that research trends reflect a general interest in the integration of AI in experimentation in science teaching, signifying reforms in the field of education. AI is redefining the role of experiments in developing scientific literacy. Its functions and possibilities can enhance elements such as inquiry, modelling, and hypothesis testing, which are foundational in experiment implementation and science subjects. Simultaneously, it provides opportunities for innovation through novel teaching practices and activities oriented towards student-centred learning, inclusion, equity, metacognition, and STEAM literacy (Cheung et al., 2024; Donthu et al., 2021; Jia et al., 2023; Öztürk et al., 2024; Park et al., 2023; Tang et al., 2024).

These trends are shaped by publications predominantly originating from specific countries and particularly from computer science research centres, institutions, or faculties. While educational institutions and departments contribute to this domain, their output is less frequent. This raises concerns regarding the actual implementation of AI in educational settings (Akhmadieva et al., 2023; Genc & Kocak, 2024; Ng et al., 2024; Zhang, 2021). A more focused, strategic alignment of education policy may be required with the integration of AI in experimentation for science teaching, achievable through professional development, training, appropriate curricula, supportive environments, and funding (Akhmadieva et al., 2023; Almasri, 2024; Öztürk et al., 2024).

Before generalizing these conclusions, it is essential to acknowledge the limitations of this study, which employs a bibliometric approach and focuses on research trends. Future research should triangulate this data with formal education documents or the opinions of policymakers, educators, and stakeholders. Nevertheless, this study affirms that AI's influence on experimentation in science teaching is undeniable and complex, as evidenced by the trends (Cohen et al., 2017; Donthu et al., 2021).

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Part 4 / Strand 4

Digital Resources For Science Teaching And Learning

Co-editors: *Nathalia Helena Azevedo & Leticia Garcia-Romano*

Part 4 / Strand 4 Digital Resources For Science Teaching And Learning

Design, evaluation and characterization of innovative resources, technological applications, digital tools, software, and environments for teaching/learning science, e.g., ICT and TEL in science education. Includes online learning environments, simulation, modelling tools, virtual and/or remote laboratories, game-based tools; self-regulation, reflection, and collaboration in digital learning environments; and implementation of machine learning, augmented reality, and artificial intelligence into teaching/learning science.

Sub-themes:

1) Integration of Augmented, Virtual, and Extended Reality in Science Education
2) Artificial Intelligence Applications in Science Education
3) Machine Learning Applications in Science Education
4) Development and Evaluation of Simulations and Digital Learning Environments
5) Game-based Learning Tools for Science Education

Contents

Strand 4: Digital Resources For Science Teaching And Learning 189

Examining The Generalisability Of Trained Computer Vision Models For Instructional Support In Science Experiments 192

Partners In Science Lesson Planning: GenAI-Driven Design With Human-In-The-Loop Validation 197

Game-Based Learning In Computer Science Lectures – A Study In Higher Education 205

Activating Epistemic Emotions To Enhance Student Engagement In Socio-Scientific Issues Through Digital Curation 213

A New Paradigm For Science Lesson Planning: Adaptive Expertise And Generative AI Integration 222

Conception Of Inclusive Learning Environments Related To Biodiversity And Geodiversity: An Innovative Project For Pre-Service Teachers 227

Bridging Digital And Physical Worlds: Leveraging AR And AI For Personalized Science Education In Geography And Astronomy 233

Talking To Or Talking Through Teachers - An Analysis Of A Digital Teacher's Guide 238

The Relationship Between Critical Thinking And Generative Artificial Intelligence: A Two-Way Street For Science Education 244

Exploring The Use Of ChatGPT In Science Lesson Planning 253

Artificial Intelligence In Teacher Education: Attitudes, Usage, And The Road To AI Literacy 263

Augmented Reality For Chemistry Education: Visualizing The Invisible In The Nitrogen Biogeochemical Cycle – A Pilot Study 274

Beware The Slider's Range: A Design Lesson From Physics Simulation Development 282

What Factors Influence Pre-Service Science Teachers' Ethical Use Of ChatGPT? 292

Generative AI Training For Pre-Service Teachers: Impacts And Adoption Patterns 297

Design-Based Research To Create A Collaborative Game To Foster Spatial Skills: The Role Of Teachers 303

Designing Digital STEM Teaching-Learning Sequences By Primary Pre-Service Teachers 308

Digital Experimental Protocols And Literacy: Interventions For More Learner Support In Science Education 316

Potential Of ChatGPT As A Pedagogical Tool In Biology Education: Enhancing Student Engagement And Critical Thinking 322

How To Teach Science To 3-6-Year-Old Pupils: Pre-Service Teachers' Perceptions Of Immersive Training With 360° Classroom Videos 329

Learning Through Comics And Students' Stress In Physics: An EDA Approach 338

Building Bridges: AI Custom Chatbots As Mediators Between Mathematics And Physics 344

ESERA 2025 Copenhagen

Strand 4: Digital Resources For Science Teaching And Learning

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Technologies In Dialogue Across Sections

This collection brings together 22 articles that explore the growing presence of digital technologies in science education research and practice. Although the studies differ in terms of educational level, disciplinary focus, methodological approach, and technological tools, they collectively reflect an ongoing effort to understand how digital technologies are shaping learning experiences, student engagement, and teacher education in science-related fields. Across the collection, technologies such as generative artificial intelligence, virtual and augmented reality, digital games, simulations, multimodal resources, and online instructional platforms appear as elements that reorganise classroom interactions, pedagogical practices, and forms of participation in science learning.

The recurring presence of artificial intelligence immediately stands out. In just a few years, AI-based tools have moved from technological curiosity to a dominant topic in conferences and journals in the field. Several papers here follow this movement by investigating the use of customised chatbots, ChatGPT, and generative AI for lesson planning and the preparation of future teachers. Still, perhaps the most interesting aspect of the collection is that the papers do not adopt a homogeneous stance toward these technologies. Rather than announcing radical transformations or replacing pedagogical discussions with technological enthusiasm, the studies seek to observe how teachers and students use these tools in teaching situations. In this sense, the papers help compose a picture of the field of experimentation, seeking to understand both the possibilities and the limitations of these new digital mediations. The collection can therefore be read through three broad thematic axes that cut across the different contributions.

Artificial Intelligence, Teacher Education, And Pedagogical Mediation

The first group brings together studies focused on the use of generative artificial intelligence in teaching and teacher education contexts. This includes investigations into customised chatbots in Mathematics and Physics education, inquiry-based activities mediated by ChatGPT in Biology classes, lesson planning with generative AI, teacher preparation, and discussions surrounding AI literacy. Despite the diversity of contexts, the papers converge in several ways. First, AI appears as a tool to support, reorganise, or expand certain pedagogical practices. The most interesting results emerge when there is some form of intentional teacher mediation, creating opportunities for students to move beyond rapid, instrumental uses of these tools toward more elaborated, exploratory forms of questioning once they receive guidance on how to interact with the technology.

Another recurring aspect concerns teacher education amid the rapid spread of these tools. Some studies suggest that future teachers express interest in and openness to AI use, while also expressing uncertainty about ethical issues, authorship, information reliability, and institutional boundaries surrounding its use. The papers reveal how AI reopens longstanding educational

discussions related to teacher autonomy, the role of pedagogical mediation, and the broader meanings of school learning.

Immersion, Engagement, And Affective Dimensions Of Learning

A second axis groups papers that explore immersive technologies and multimodal languages to enhance student engagement. This includes studies on 360° videos for teacher education, virtual reality, augmented reality, hybrid games, and digital curation in socio-scientific issues. What these studies share is a focus on students' experiences during the learning process. Their interest extends beyond conceptual gains to encompass motivation, stress, participation, immersion, and emotional involvement. The study on comics, for example, suggests that narrative and visual formats may help create less stressful learning environments for students. Meanwhile, studies on virtual reality and hybrid games investigate how more interactive, embodied experiences can bring students and teachers closer to inquiry-based STEM practices.

At the same time, the papers show that incorporating these technologies also entails concrete limitations and tensions. Participants report physical discomfort during immersive experiences, while other studies highlight the need for careful planning to prevent technology from becoming merely a source of distraction or spectacle. What emerges from this group of papers is an attempt to understand the conditions under which these tools may contribute to more meaningful learning experiences.

Digital Materials Design And The Organisation Of Teaching Practices

The third axis brings together studies focused on the design of digital materials, activities, and environments for science education. These include research on digital laboratory reports, STEM teaching sequences developed on digital platforms, physics simulations, digital learning objects, and digital teacher guides. These studies are connected by a shared concern with the organisation of pedagogical practices and the ways in which different digital formats influence learning. Some investigate issues related to cognitive load and visual design, while others analyse how pre-service teachers structure inquiry activities within digital environments.

Interestingly, several of these studies point to a recurring tendency: even in technologically innovative contexts, highly guided, linear approaches still predominate. Convergent activities, structured sequences, and more controlled forms of inquiry appear frequently in participants' materials. This does not diminish the relevance of these proposals, but it suggests that technological changes are not always accompanied by equivalent shifts in pedagogical conceptions.

Looking Ahead With Open Questions For Technology And Science Education

The papers in this collection portray a field undergoing rapid transformation while still marked by important continuities. Questions related to student engagement, teacher education, the organisation of school scientific inquiry, and pedagogical mediation remain central, even as new technologies increasingly occupy a visible place in research. Perhaps for this reason, the main contribution of this collection lies in documenting how researchers and teachers are attempting to negotiate the possibilities and limitations of these technologies in real teaching contexts.

At the same time, the collection also makes visible a series of open questions that may guide future research. Many studies demonstrate how digital technologies can support engagement, participation, immersion, or instructional design, but less attention is given to the broader institutional, political, and economic conditions shaping the adoption of these technologies in schools and teacher education programs. As digital platforms, generative AI systems, and data-

driven educational tools become increasingly embedded in educational systems worldwide, questions about dependence on private technological infrastructure, data governance, platformization, and commercial interests become difficult to ignore.

A more explicitly critical perspective on technology and science education still has significant room to develop within the field (Garcia-Romano et al., 2021). Future studies may increasingly need to ask whose interests are served by particular technological agendas, which forms of knowledge and participation become privileged, and which educational practices risk becoming marginalised. These questions become especially relevant in the context of the ongoing neoliberalization of education across different parts of the world, where efficiency, personalisation, scalability, and performativity often shape educational innovation agendas.

As schools and universities continue to incorporate AI systems, immersive environments, and digital learning platforms into everyday practices, science education research may benefit from approaches that also examine how technology reshapes relationships between teachers, students, institutions, knowledge production, and educational policy (Azevedo and Santos, 2025). In this sense, the studies gathered here may also be read as part of a larger conversation about the future of science education itself: a future in which technological change is likely to remain central, but where pedagogical, ethical, and political questions will continue to demand careful and critical attention.

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Examining The Generalisability Of Trained Computer Vision Models For Instructional Support In Science Experiments

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When science teachers facilitate conduct of student experiments, they face challenges in monitoring students' procedural steps due to presence of multiple students and limited cognitive bandwidth. Yet, without adequate teacher supervision, students' procedural missteps, incorrect experimental techniques, and safety violations become missed teacher observations that can result in the formation of undesirable student practices. To address this, computer vision can be deployed in science laboratories to continuously monitor students' procedural steps and highlight relevant student information for teachers to intervene. However, the generalisability of trained computer vision models for instructional support in science experiments is untested. To this end, we examined the performance of a trained computer vision model (SlowFast) on YouTube videos. The SlowFast model was trained on videos collected from 140 middle school students (which is of a specific population and context), and the gathered YouTube videos consists of 77 individuals from a wide variety of populations and contexts. Results indicate that model generalisability depends on choice of pretrained model and size of training dataset, together with recording conditions and data consistency of the new context. More specifically, precaution ought to be taken to ensure that collected training data contains at least hundreds of training instances, and that camera setup in all contexts are of similar viewpoints and zoom factors. Furthermore, variations in training instances should imitate expected variations in different contexts. Overall, this work attained preliminary evidence of the general feasibility of deploying trained computer vision models for instructional support in science experiments.

Keywords: Artificial Intelligence, Laboratory Instruction, Science Education

Introduction

When science teachers facilitate the conduct of student science experiments, they face challenges in monitoring students' procedural steps. This is because in a typical science laboratory setting, science teachers are tasked with attending to the learning needs of several students, and as humans, they experience natural cognitive limits in being able to pay sufficient attention to every action taken by each student (Sherin & Star, 2011). Yet, awareness of students' procedural steps is critical for science teachers to be able to provide students with suitable formative feedback on their experimental work (Stiggins, 2006). Without adequate teacher awareness, students' procedural missteps, incorrect experimental techniques, and safety violations become missed teacher observations that can result in the formation of undesirable student practices.

In this case, there exists a teacher observation gap that can be fulfilled with the use of artificial intelligence (AI). Specifically speaking, computer vision models can be deployed in science laboratories to continuously monitor students' procedural steps and highlight relevant student information for teachers to intervene (Chng, 2024). However, training of computer vision models is sensitive to data inputs (Gudivada et al., 2017) and the generalisability of trained computer vision models for instructional support in science experiments is untested. In particular, it is unknown if a computer vision model that is trained with a specific set of student data can perform well in the observation of another population in another context. With this in mind, this research

work seeks to examine the generalisability of trained computer vision models so as to establish the general feasibility of deploying AI for instructional support in science experiments.

Methods

Our research question asks, "What is the generalisability of a trained computer vision model in conducting student observations from another population and context?" As detecting students' procedural steps is the primary concern for teachers during science experiments, we focus on the generalisability of action recognition models in this research.

Our chosen action recognition model is that of SlowFast (Feichtenhofer et al., 2019). In terms of model performance, SlowFast belongs to the latest generation of models that have demonstrated state-of-the-art capabilities for action recognition (Fan et al., 2021). In terms of model architecture, SlowFast is "partially inspired by biological studies on the retinal ganglion cells in the primate visual system" (Feichtenhofer et al., 2019, p. 6203) and mimics the way in which visual information is processed by humans. With these advantages in mind, we target SlowFast as the intended computer vision model for our generalisability test. A SlowFast model that was pretrained with the Kinetics400 dataset (Kay et al., 2017) was downloaded from the PyTorchVideo library (Fan et al., 2021). The motivation for using a pretrained model is due to the fact that such models contain primitive understandings of lower-level action features (Sharif Razavian et al., 2014), which renders them easier to train and adapt for our purposes (Tajbakhsh et al., 2016).

Table 1. **Statistics of video clips in our video datasets**.

Action ID	Student Action	Number of Student Video Clips	Number of YouTube Video Clips	Action Category
1	close air hole	117	55	Light Bunsen burner
2	close gas tap	166	74	
3	ignite Bunsen burner	367	84	
4	open air hole	253	60	
5	open gas tap	220	72	

Our target set of student actions is related to the lighting of a Bunsen burner (see Table 1 for detailed list of actions). This set of student actions was chosen because lighting Bunsen burner is a common procedure in science experiments. To prepare our downloaded SlowFast model for test of generalisability, we first train it with videos collected from 140 middle school students as they light a Bunsen burner. With the trained model, we then evaluate its performance on YouTube videos of 77 individuals lighting a Bunsen burner. YouTube was selected as a source for our generalisability test since it contains videos of individuals from a wide variety of populations and contexts. In other words, we can address our research question by examining the YouTube performance of a SlowFast model that was trained on data collected from a middle school (which is of a specific population and context, as compared with YouTube videos which is of a wide variety of populations and contexts). Findings from this investigation will ultimately apprise us

of the need to retrain action recognition models for use in other science experiments and provide us with an appreciation of the general feasibility of deploying AI for instructional support in science experiments.

Table 1 shows the statistics of video clips in each of our video datasets (i.e., student dataset and YouTube dataset). Each video clip represents an uninterrupted instance of a particular action taken by the student/individual within the video. Since each action can possibly be taken by the student/individual more than once or none at all, the number of video clips obtained for each action deviates from the total number of videos collected in each dataset.

Results

Table 2 shows the class prediction accuracies of our trained SlowFast model on YouTube videos. Surveying Table 2, our model's class prediction accuracies are consistently above 70% and has an overall accuracy of 76.81%. Compared with Slowfast's reported state-of-the-art accuracy of 76.94% (Fan et al., 2021), our model's performance on the unseen YouTube dataset with different populations and contexts is respectable. This is possibly because our trained SlowFast model reaped the performance benefits of being pretrained with the Kinetics400 dataset to learn lower-level action features and being further trained with a sizeable student dataset to learn our target set of student actions. It is noteworthy here that the reported state-of-the art accuracy was attained with a dataset that contains at least 400 video clips for each action class (Fan et al., 2021). By contrast, our smallest action class (i.e., "ID 1 close air hole") only possessed 117 video clips and our largest action class (i.e., "ID 3 ignite Bunsen burner") contains no more than 400 video clips. Yet, our trained model is able to perform on unseen data with a class prediction accuracy of 80.00% for our smallest action class and achieve an overall model accuracy of 76.81%. This signals the importance of transfer learning for AI models and hints at the general feasibility of deploying trained AI models for use in other science experiments. On balance, our test on data from the wild (i.e., YouTube videos) demonstrates the generalisability of trained computer vision models as long as the choice of pretrained model is appropriate and the size of training dataset is sufficient.

Table 2: Class prediction accuracies of our trained SlowFast model on YouTube videos.

Action ID	Student Action	Class prediction accuracies
1	close air hole	80.00%
2	close gas tap	78.38%
3	ignite Bunsen burner	83.33%
4	open air hole	70.00%
5	open gas tap	70.83%
-	Overall	76.81%

In an effort to better understand model generalisability, I further investigated examples of incorrect model predictions qualitatively. In this respect, two inherent sources of model confusion were discovered. First, even though the camera viewpoint and zoom factor of our collected student videos is fixed, those of YouTube videos can be changing. For instance, some YouTube videos provide a shifting perspective as the Bunsen burner is being lit (e.g., from front to side). Otherwise, some YouTube videos zoomed in on the gas tap when it is being opened or closed and later zoomed out to reobtain a full view. By contrast, all of our student videos adopted an all-

encompassing frontal viewpoint with unvarying zoom. Second, the apparatus used in school science laboratories may differ from that of YouTube videos. For example, gas lighters appeared in all our student videos, but certain YouTube videos featured spark lighters. Altogether, these differences in recording conditions and apparatus used resulted in more incorrect model predictions when contexts are switched, which serves to remind us that model generalisability is dependent on recording conditions and data consistency as well.

Discussion

In contemplating the widespread deployment of trained AI models, we think about the implications of our investigation findings and deliberate on the integration of computer vision models for instructional support in science experiments. From our model investigation, it became evident that model generalisability depends on the choice of pretrained model and the size of training dataset, together with the recording conditions and data consistency of the new context. Consequently, we should take precaution to ensure that collected training data contains at least hundreds of training instances for each action class, and that camera setup in all contexts are of similar viewpoints and zoom factors. Furthermore, as with common machine learning approaches, variations in training instances should imitate expected variations in different contexts. For example, if both spark and gas lighters are expected to be found within deployment contexts, then gathered training instances ought to contain ignition of Bunsen burner with both spark and gas lighters. In this way, widespread deployment of AI models in general science experiments can be achieved without concerns for reduced performance in new contexts.

As for the integration of computer vision models for instructional support in science experiments, we note that teachers face severe time constraints in schools and would not possess sufficient bandwidth to go through model outputs for every student (Chng, 2024). Under these circumstances, the delivery of instructional support should include added processing steps to consolidate pertinent information for teachers. More specifically, we can apply auxiliary algorithms to extract needed student information from detected student actions. For instance, if teachers wish to track the order of procedural steps taken by students for formative feedback, then we can rely on sequence analysis (Mannila et al., 1997) to ascertain order of student actions and highlight to teachers whenever students deviate from expected sequences. In essence, the integration of computer vision models for instructional support should take into consideration the realities of teacher circumstances and pedagogical concerns so as to promote widespread deployment of AI models in general science experiments.

Finally, although we have attained preliminary evidence of model generalisability in this investigation, more testing is required to establish the parameters and boundaries of general applicability. Specifically, more research work is needed to uncover the nuanced performance of trained AI models across different experiments, for diverse students, and in varied environments.

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Partners In Science Lesson Planning: GenAI-Driven Design With Human-In-The-Loop Validation

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Generative Artificial Intelligence (GenAI) has emerged as a disruptive technology with vast potential in education. A workshop that took place during the ESERA 2025 conference explored the intersection of GenAI and science education, focusing on how educators utilize GenAI tools to develop lesson plans that consider students' common alternative frameworks. We investigated the awareness and adoption levels of GenAI among science educators, explored how researchers and practitioners use GenAI to construct science lessons, and assessed how collaboration with other experts in science education and research can validate and enhance instructional design developed with GenAI. During the workshop, participants engaged in hands-on activities using a customized GenAI tool, allowing them to design instructional material tailored to their specific educational needs. This session emphasized the importance of integrating scientific accuracy and pedagogical principles in exercise design, and discussions centred on best practices for leveraging GenAI in educational contexts while addressing potential concerns and limitations. The workshop equipped participants with a comprehensive understanding of GenAI's potential in science education and served as a stepping stone towards developing more effective, personalized, and engaging teaching environments.

Keywords: Generative Artificial Intelligence; Human-in-the-loop; Students' alternative frameworks

Introduction

Generative Artificial Intelligence (GenAI) has emerged as a disruptive technology with vast applications across various domains, including education. GenAI offers opportunities to create more engaging, personalized, and effective learning environments (Meli et al., 2024). From the educator's perspective, integrating GenAI streamlines instructional material development, reduces instructor workload, and enhances material quality (Dickey & Bejarano, 2024).

GenAI can potentially assist educators in generating instructional materials and supplementary resources tailored to the curriculum and individual student needs (Bonde, 2024). While previous research has explored various applications of GenAI in educational settings, there remains a need for further investigation into its potential for supporting instructional design in a structured and efficient manner (Karpouzis et al., 2024). The integration of GenAI into science education may present a significant opportunity to transform lesson planning, not only by enhancing its feasibility and robustness for educators but also by increasing educators' awareness of students' learning requirements within the context of the scientific content they must acquire (Almasri, 2024).

While educators may acknowledge that GenAI potentially facilitates and enhances their work, concerns persist regarding the limitations of this emerging technology, particularly in disciplines where the model's training data are insufficient. To mitigate these risks, it is crucial to maintain a "human-in-the-loop" approach, which generally refers to the need for human interaction, intervention, and judgment to control or change the outcome of a process (Meng, 2023, p.1). This

ensures that critical decisions are not left solely to automated systems and allows for the detection and correction of potential mistakes or unintended consequences and the improvement of the overall outcome quality (Chen et al., 2023).

Addressing these multifaceted opportunities and challenges, the workshop held during the ESERA 2025 conference aimed to transcend individual trials and provide structured guidance and support to assist educators in enhancing their awareness of GenAI capabilities (Bonde, 2024). Specifically, it sought to facilitate the utilization of GenAI for context-specific needs, particularly for developing lesson plans that incorporate relevant pedagogical aspects. Additionally, the workshop intended to expose participants to the "human-in-the-loop" methodology, where the human is an expert in teaching a specific scientific topic, to validate and enhance the results they co-created with GenAI.

Theoretical framework

Addressing students' alternative frameworks is essential for designing effective science education. Educators are expected to engage students in activities that challenge their ideas and promote conceptual change toward a scientifically accurate understanding of the world (Vosniadou, 2011). This aligns with the emphasis on integrating science practices and developing sophisticated teaching methods to support student learning (Arias et al., 2016).

However, traditional textbooks and guidelines often focus more on scientific content, rather than on the alternative frameworks students may employ in their interpretations (Zourmpakis et al., 2023). Consequently, embracing more progressive pedagogical approaches challenges science educators at an individual level as they frequently encounter diverse content and varying levels of complexity that are often related to a broad spectrum of alternative frameworks (Johsua & Dupin, 1991).

In this respect, GenAI shows the potential to accelerate educators' lifelong learning progression and effectively support them in implementing their day-to-day educational duties (Pantazatos et al., 2024). GenAI tools introduce new methodologies for effective teaching and learning, addressing traditional educational challenges. This technology can empower educators to develop dynamic teaching materials, fostering innovation in educational practices and facilitating ongoing learning and skill development. Adopting GenAI in education can transform instructional design by analysing and expanding subject-specific content and creating learning pathways informed by educational research (Meli et al., 2024).

Integrating GenAI into science education presents a promising avenue for enhancing teaching methodologies and addressing students' alternative frameworks. GenAI can simulate complex physical phenomena and provide visual and interactive learning experiences, which are often challenging to replicate in traditional classroom settings. By leveraging GenAI, educators can personalize their teaching by streamlining their workflow, creating more efficient lesson plans, generating diverse problem sets, and developing tailored explanations for complex concepts. This technology can assist in identifying and targeting common areas of alternative conceptions among students, allowing for more effective instruction (Cooper, 2023). In teaching planning, GenAI can direct educators to consider established knowledge in the discipline they teach and in the discipline of teaching it. This can enhance their awareness of using their own PCK in planning and conducting their teaching.

Concurrently, implementing GenAI in educational contexts presents several significant challenges (Alier et al., 2024). The efficacy of the models underlying GenAI depends heavily on the quality of user-provided prompts. The caliber of responses can exhibit considerable variability

based on the application domain, potentially resulting in inconsistent or inadequate information in certain areas. The underlying models can generate content that appears authoritative but may be entirely fabricated or irrelevant to the query, which can be misleading in educational settings. The responses may perpetuate biases and reinforce stereotypes present in the training data. Finally, from a personal development aspect, there exists a risk of diminished creativity and critical thinking among users due to excessive reliance on the outputs that GenAI can readily produce. While the respective tools can assist, they cannot supplant the value of human interaction, crucial for users' development.

Mitigating the risks of GenAI in education requires a multifaceted approach that addresses ethical, pedagogical, and technological concerns. Developing critical GenAI literacy among educators is crucial for responsible innovation and informed use of GenAI (Rudolph et al., 2024). This involves fostering an environment where stakeholders can understand and critically evaluate GenAI-generated content. Maintaining human oversight is essential to address potential privacy, bias, and accuracy issues in GenAI tools (Noroozi et al., 2024). Human-in-the-loop approaches, informed by experts' input, can solve problems related to data scarcity, feedback accuracy, annotation costs, and decision-making reliability in educational material development. Combining human expertise with artificial intelligence capabilities offers promising solutions for creating more effective and efficient educational tools and experiences (Chen et al., 2023).

To complement these theoretical considerations, further inquiry is needed into how researchers or practitioners and institutions can critically and productively integrate GenAI into science instruction. Several open questions emerge as particularly relevant to ongoing research and practice:

1. What would effective integration of GenAI tools into teaching planning and delivery look like, and what improvements might it bring to instructional quality and educator workload?
2. How can GenAI be leveraged to identify and address students' alternative frameworks, or other considerations embedded in science education, in supporting deeper conceptual understanding?
3. What strategies can be employed to combine human expertise and GenAI to ensure that instructional materials are both pedagogically sound and scientifically accurate?
4. How might additional human input—through peer collaboration, student feedback, or expert review—be used to maintain the quality and integrity of GenAI-generated content in educational contexts?

These questions not only reflect the pedagogical tensions and opportunities surrounding GenAI but also help frame future empirical studies and practical design considerations in science education.

Method

To explore and exemplify a means to address the questions above, we organized a workshop as part of the ESERA 2025 conference. The workshop engaged the participants with GenAI tools for lesson planning, while emphasizing educator agency, peer collaboration, and reflection. In essence, the workshop served as a pilot implementation of an educator-centred GenAI approach in science education.

Participants And Context

The workshop brought together higher education science researchers and practitioners (*N*=25) from diverse backgrounds, most of whom were curious about using GenAI but had limited prior experience. An initial poll confirmed that less than half had experimented with tools like ChatGPT, roughly mirroring the split found in larger surveys (e.g., Pantazatos et al., 2024) on GenAI adoption. This mix provided a rich environment for peer learning. The focus on science education (as opposed to general teaching) allowed us to tailor scenarios to common science topics and students' alternative frameworks, making the experience directly relevant to participants' real-life contexts.

Workshop Design

We structured the 45-minute session into four interactive phases aligned with the human-in-the-loop design: orienting and framing GenAI use, hands-on experimentation, collaborative expert review, and reflective synthesis.

Orientation And Critical Framing

The workshop began with a brief introduction to GenAI's capabilities and limitations, using current research and classroom examples to provoke reflection. We demonstrated GenAI's potential to simulate scientific phenomena and its tendency to state confidently scientific errors. Framing was informed by literature highlighting GenAI's epistemic risks (e.g., Cooper, 2023; Rudolph et al., 2024), setting a tone of curiosity paired with critical literacy. Participants shared their hopes and concerns in an open dialogue: many were enthusiastic about reducing lesson-planning load, while others voiced concerns about delegating too much conceptual work to GenAI or inadvertently circulating misconceptions. This ideas exchange helped establish the workshop's central tension: how to meaningfully integrate GenAI without surrendering pedagogical judgment.

Hands-On GenAI Tool Use

Participants then logged into a fine-tuned GenAI tool interface developed by our team. The tool was inspired by prompt-engineering systems like that of Karpouzis et al. (2024), and invited users to input topics, student level, known alternative frameworks, and teaching preferences. Based on this, the tool generated a structured lesson plan, typically including: (1) learning objectives, (2) an introductory warm-up targeting a common alternative framework, (3) an interactive activity, and (4) an assessment item. To scaffold engagement, we pre-loaded one editable prompt that served as a model:

> Design a 60-minute lesson plan for first-year university students focusing on the First Law of Thermodynamics, particularly energy change and energy conservation.
>
> Address common alternative frameworks such as the idea that energy is 'used up' or disappears during a process. The lesson should support students in developing a correct understanding of energy conservation through both conceptual and quantitative reasoning.
>
> Include: (1) a context-rich example involving heat and work (e.g., gas expansion, heating a metal block), (2) a guided problem-solving activity, and (3) a checkpoint for discussion where students compare their initial ideas with formal thermodynamic reasoning.
>
> Conclude with a summary that reinforces the conservation principle across system boundaries.

Participants worked in pairs to simulate collaborative use, actively revised outputs, applying their pedagogical knowledge to fill in gaps or correct inaccuracies, demonstrating the central role of

educator judgment in human-in-the-loop design. As they interacted with the tool, facilitators supported prompt refinement (e.g., adding context, specifying alternative frameworks). Participants were reminded that GenAI outputs were first drafts to be evaluated critically. Educators noted several emergent patterns: some plans were praised for creative analogies (e.g., comparing chlorophyll to a "solar panel"), while others lacked experimental rigor (e.g., omitting control variables in suggested investigations).

Human-in-the-Loop Validation Exercise

Following initial design work, groups submitted a selected lesson plan for live review by a science education researcher (co-facilitator), modelling expert oversight. The reviewer projected excerpts from a participant-generated plan and engaged in a public "think-aloud," identifying both strengths and areas of concern. For instance, a proposed analogy about current flow was deemed accessible but conceptually imprecise; the expert revised the phrasing on the spot. Positive design features were also highlighted, such as an GenAI-suggested student role-play where learners acted as parts of a circuit. This segment gave participants a concrete example of what human-GenAI co-design might look like in situ, reinforcing the necessity of content validation. Feedback from attendees suggested this was one of the most impactful workshop moments, providing a mental model for how educators might vet GenAI-generated materials in their own practice.

Outcomes

This workshop provided participants with a structured, immersive experience at the intersection of GenAI and science education. By engaging in hands-on activities, collaborative design, and guided expert review, participants explored how GenAI can support lesson planning—particularly in addressing students' alternative conceptions. The implementation foregrounded human agency and critical engagement with GenAI, aiming not merely to showcase technological capabilities but to situate them within authentic pedagogical challenges (Zourmpakis et al., 2023; Chen et al., 2023).

By the end of the session, participants reported feeling more confident in experimenting with GenAI tools for educational purposes. Many articulated a shift in mindset, from skepticism or apprehension to a more empowered and strategic view of GenAI use. As one participant remarked, "I was worried AI would take over, but now I see it's up to me to direct it. It's like a super-smart apprentice – helpful, but it still needs supervision." This comment reflects a broader theme that emerged across reflections: GenAI, when used thoughtfully, can extend educator capacity without displacing professional judgment.

Participants left the workshop with concrete lesson plan drafts (customized to their classroom context and structured using the GenAI tool) that could be further refined for actual use. Several noted that the tool had helped them generate ideas they might not have considered otherwise, affirming literature on GenAI's role in ideation support and workload reduction (e.g., Pantazatos et al., 2024). Yet this creative potential was matched by a shared recognition of GenAI's limitations. All participants identified at least one factual error, omission, or pedagogical mismatch in the GenAI output, reinforcing the necessity of educator oversight. This outcome was viewed positively: the experience functioned as a form of inoculation against uncritical use of GenAI, strengthening participants' critical GenAI literacy.

The workshop also illuminated the dynamics of educator agency and collaboration. Educators who initially expressed low confidence in using GenAI tools showed greater enthusiasm and initiative when paired with peers. This suggests that co-use scenarios not only improve outcomes but also reduce intimidation, highlighting peer collaboration as a key factor in building collective

confidence and competence. Furthermore, the visible role of the invited science education researcher (as a constructive and approachable "critical friend") helped normalize the idea that integrating GenAI into practice is a shared, iterative process. Participants responded positively to this modelling of expert feedback, indicating openness to seeking similar validation mechanisms in their own contexts.

In sum, the workshop outcomes support the viability of a teacher-centred, human-in-the-loop approach to GenAI in science education. Participants valued the time-saving and creative affordances of GenAI, while also deepening their appreciation for the irreplaceable role of human judgment. These insights not only confirm existing hypotheses in the literature but also offer direction for future implementations, particularly the need to scaffold peer collaboration, embed expert review, and foster critical literacy as core components of any GenAI-supported instructional design process.

Discussion

The findings of this workshop-based study offer valuable insights into the evolving role of GenAI in science education, particularly when implemented through a human-in-the-loop, teacher-centred design. As the results illustrate, educators engaged with GenAI not merely as consumers of pre-generated content but as critical co-designers, actively shaping and refining outputs in response to pedagogical needs. This aligns with existing calls for educators to retain epistemic authority in the classroom, even in the presence of increasingly sophisticated AI tools (Cooper, 2023).

The varied responses to GenAI-generated lesson plans underscore a central theme in the literature: that while GenAI offers substantial affordances (such as idea generation, time efficiency, and personalized content creation) it also demands rigorous human oversight to mitigate the risks of inaccuracy, superficiality, and bias (Alier et al., 2024; Noroozi et al., 2024). Participants' recognition of these risks and their capacity to critique and improve the GenAI outputs reflect the growing importance of critical GenAI literacy in educator professional development (Rudolph et al., 2024). Rather than viewing GenAI as a threat to educator autonomy, many participants reframed it as a tool requiring pedagogical steering—consistent with the "super-smart apprentice" metaphor voiced during the session.

Notably, the workshop demonstrated how GenAI might be harnessed to better address students' alternative frameworks in science. By prompting the GenAI to design warm-ups and activities that target known alternative frameworks, participants practiced a generative form of lesson planning aligned with constructivist goals and conceptual change theory (Vosniadou, 2011; Arias et al., 2016). This suggests that when GenAI is guided by well-crafted prompts and supported by expert or peer knowledge, it can serve not only to expedite instructional design but also to embed more responsive and diagnostic pedagogical strategies.

In this regard, the findings also validate the theoretical potential of GenAI as a tool for accelerating educators' professional growth (Pantazatos et al., 2024; Meli et al., 2024). Participants' experiences echo research suggesting that GenAI-powered platforms can scaffold educators' reflection and creativity, provided they are used in contexts that value human interpretation over automation. The design of the workshop—emphasizing peer collaboration and expert validation—resonates with broader literature advocating for multi-layered human input in educational GenAI systems (Chen et al., 2023). The observed benefits of pair work among less confident participants further emphasize the need to structure GenAI training within socially

supported collaborative environments that promote collective educator agency.

At the same time, the workshop exposed important design tensions. For instance, the variability of GenAI outputs highlighted the ongoing challenge of prompt precision (Alier et al., 2024), and participants' mixed trust in GenAI-generated facts mirrored broader concerns about misinformation and fabricated content. This reinforces the notion that GenAI's value lies not in its autonomy but in its ability to extend human thinking, provided researchers and practitioners are equipped to filter, contextualize, and critique its suggestions.

Ultimately, this study contributes to a growing body of evidence indicating that successful integration of GenAI in education requires more than access to tools—it requires frameworks for thoughtful, ethical, and collaborative use. As such, it affirms that teacher-centred, critically reflective approaches are not only compatible with GenAI but essential for its responsible and pedagogically sound implementation.

Conclusions

This study contributes to the emerging landscape of GenAI in science education by demonstrating how teacher-centred, human-in-the-loop approaches can enable thoughtful integration of AI into lesson planning. The workshop highlighted that while GenAI offers clear benefits, such as efficiency, idea generation, and flexible adaptation, it must be embedded within pedagogical frameworks that prioritize human judgment, contextual relevance, and critical oversight.

Participants' experiences affirmed that educators are eager to explore GenAI, but they require structured opportunities to build confidence, develop prompt literacy, and collaboratively review outputs. These findings support a vision of GenAI not as a replacement for researcher or practitioner expertise, but as a partner in pedagogical design; one that, when properly guided, can enhance science instruction and help address persistent challenges such as student alternative frameworks.

Looking ahead, future work should explore longitudinal implementations of teacher-GenAI co-design, particularly across varied school contexts and subject areas. Developing professional development models that promote peer collaboration, expert feedback, and iterative refinement of GenAI-generated content will be key. Additionally, more research is needed into how GenAI can support formative assessment, differentiation, and inclusive pedagogy. As GenAI tools continue to evolve, the education community must remain committed to evaluating their impacts, not only on efficiency and design quality, but also on educator identity, student understanding, and the broader ethics of AI-enhanced teaching.

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Game-Based Learning In Computer Science Lectures – A Study In Higher Education

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In higher education, incentivizing approaches are shifting from traditional teaching to constructivist, self-determined learning methods. The latter allow students to study at their own pace and focus on individual needs. One such approach is game-based learning, which is understood as the use of games for educational purposes. Based on predetermined learning objectives, such serious games are specifically designed to foster learning by playing educational games. Considering digital transformation of learning materials, serious games are often realized as digital games. These are considered particularly suitable for students with prevalent engagement with computers and high understanding of digital tools, such as computer science students. Within the scope of an elective subject at the faculty for Business Informatics at the University of Applied Sciences Karlsruhe, Germany, digital serious games were introduced as an integral part of the lectures. Over the course of 3 semesters, these educational games were evaluated by students. In total, n=87 higher education computer science students participated in the study. Results shed light on students generally expressing enthusiasm as well as appreciation for educational games. Students respond positively to the adoption of innovative game-based teaching methodologies. There is a notable appreciation for the replacement of traditional unidirectional teaching methods. In addition to providing positive feedback, students offer suggestions for the enhancement of digital serious games regarding their utilization, incorporation into lectures, and game design. Students indicate that digital serious games are enjoyable and anticipate their incorporation into future curricula. This article delves into the survey results and provides recommendations for further application of game-based learning in higher education.
Keywords: Constructivism, Digital Learning, Student Engagement

Introduction

In the contemporary era, a decline in the attention span of students has been observed. This leads to educators seeking innovative methods to gain students' attention and interest in lectures. The integration of incentivizing approaches into higher education lectures has gained significant traction as to enhance student engagement, motivation, and attention (Gruber, 2025). Hence, game-based learning has evolved as a popular method for interactive learning (Bencsik et al., 2021).

Game-based learning is an established approach in higher education, especially in science, technology, engineering and mathematics (STEM) disciplines (Semmler et al., 2024). The problem-solving approach that is taught and applied in STEM disciplines can be aligned with solving problems in educational games (Ishak et al., 2021; Manzano-León, Camacho-Lazarraga, Guerrero, et al., 2021). Platforms like genially and Kahoot! have emerged as popular tools for educational games, offering interactive experiences that can transform traditional educational paradigms (Martinez et al., 2023).

Even though there are many studies on the effect of digital serious games on student motivation (Bröker et al., 2021; Ehrlich et al., 2020; O'Brien & Pitera, 2019), computer science students' perception of quiz-based digital games have yet to be investigated. Therefore, this study showcases computer science students' perception of digital educational games based on the

aforementioned platforms in higher education settings, drawing insights from survey-based studies and evidence-based research.

Background

Constructivist learning theory focusses on learners actively constructing their own understanding and knowledge of the world through experiences and reflection (Kergel & Heidkamp-Kergel, 2020). Rooted in the work of theorists like Jean Piaget and Lev Vygotsky, this theory posits that learning is a process of meaning-making rather than passive absorption of information. In other words, constructivist learning theory favours active learning and refrains from the concept of teaching. Constructivism advocates for learner-centred approaches, where students engage in problem-solving, exploration, and critical thinking, often through collaborative activities. This approach highlights the importance of prior knowledge, social interaction, and contextual learning in shaping new understandings (Vygotsky et al., 1980). Teachers act as facilitators, guiding learners to build connections between new and existing knowledge, fostering deeper comprehension and skill development (Franco & DeLuca, 2019).

Following the idea of students constructing their own knowledge and taking an active part in the learning process, constructivist learning environments focus on presenting information. The information is based on the learning objective and part of the learning content. Students process the information provided individually and reconstruct their own knowledge. In the next step, students show a certain behaviour applying their knowledge. Teachers take a supporting role in diagnosing competences as well as potential weaknesses. Monitoring students' behaviour and success, teachers modify the information and learning support offered. At this stage, the cycle of constructivist learning environment closes at the stage of information presentation (Kerres, 2024).

In accordance with the theory of constructivism, constructivist learning environments enable students to self-regulate their learning process. Working on complex and lifelike problems with minimal intervention by teachers is key (Gräsel & Gniewosz, 2011). This approach is particularly well suited to digital learning methods. As they offer students the advantage of being able to work through and access digital learning resources at their own individual pace, they support constructivist learning (van Ackeren et al., 2017). Among many digital learning methods, digital learning games are evolving as popular constructivist learning approach.

Digital game-based learning refers to the use of digital games to facilitate learning. This approach makes use of entire games, specifically designed for educational purposes addressing learning objectives. These games are referred to as serious games (Weselek, 2022). In contrast to game-based learning and serious games, gamification is defined as the use of single game elements (Deterding et al., 2011). Gamification elements and serious games can be used in a physical and in a digital environment (Gruber & Faßbender, 2025).

Regarding the conceptualization of serious games, it is of importance to consider the target group. In higher education, students often face difficulties concentrating on lecture materials (Bencsik et al., 2021). This necessitates a comprehensive understanding of the students' existing knowledge and skills. Especially the learning process needs to be considered. As digital serious games operate based on different stimuli, the internal learning process and attention span can differ from learning in traditional settings (Frey & Uemminghaus, 2021). Selective perception can cause the differentiation of how students perceive digital settings (Gagné, 1980). Therefore, it is important to communicate expectations and the purpose of digital serious games to the students.

In higher education contexts, digital serious games aim to create immersive and interactive environments that promote active learning, addressing individual learning paths by means of constructivist learning environments (Frey & Uemminghaus, 2021). The constructivist framework is particularly relevant in digital serious games, as interactive games create helpful environments for experimentation, feedback, and active learning (Kerres, 2024). Digital serious games are particularly promising for students with a high affinity for gaming in their leisure time. It is evident that this is the case for STEM programs (Fleuren, 2016; Ishak et al., 2021; Manzano-León, Camacho-Lazarraga, Guerrero, et al., 2021). Indications in the literature suggest that students' perception of and their satisfaction with the lecture can be affected by digital serious games (Priesto et al., 2021). In general, previous studies show that STEM audiences are suitable for the use of digital serious games (Buchner et al., 2022; Makri et al., 2021; Taraldsen et al., 2022).

Prominent examples for digital serious games in the context of digital game-based learning are escape games, simulations and quizzes (Gruber & Faßbender, 2025). Quizzes are tests including numerous questions as well as related pre-formulated answer sets. In a quiz, questions can be phrased either single or multiple choice (Georg, 2022). Tools for the development of quizzes utilized in higher education are g*enially* and *Kahoot!*:

- *genially* is a web-based tool offering features for creative content creation. The portfolio includes presentations, infographics and game-based learning like quizzes (Genially Web, 2023). Moreover, the platform allows for the incorporation of multimedia elements and interactive scenarios, making learning more engaging and dynamic. *Genially* has been evaluated for its pedagogical quality and is noted for increasing student engagement through gamified quizzes (Martinez et al., 2023; Sanchez & Plumettaz-Sieber, 2019).

- *Kahoot!* is a game-based learning web platform that allows educators to create quizzes and interactive lectures (Kahoot!, 2024). It is evident that the use of *Kahoot!* for educational purposes enhances constructivist learning, as the digital environment encourages learners to actively engage and construct knowledge and concepts. This allows for self-determined learning and developing students' problem-solving competences (Allegra et al., 2019).

In summary, genially and Kahoot! can contribute positively to constructivist learning in higher education. Considering the aptitude of digital serious games for STEM students, it is imperative to examine quizzes on these two platforms within the context of this study. The following section describes the research interest in more detail.

Objectives

The main objective of this project is to conduct a study on the use of digital quizzes as serious games in STEM higher education lectures. In addressing the issue of poor student engagement in recent lectures, this research is directed towards student motivation and engagement. The subordinate objectives of this project are summarized as follows:

- Creating digital quizzes based on predefined learning objectives for investigation.

- Evaluating engagement and motivation to measure the impact of these platforms in the learning process.

- Identifying challenges and limitations associated with implementing digital serious games in STEM higher education settings.

- Developing best practices to establish recommendations for effectively integrating these platforms into higher education teaching.

Based on these objectives, the following research question arises: *How do computer science students perceive digital serious games in STEM higher education?* The underlying research methodology selected for this project is outlined in the following section.

Methodology

Based on the aforementioned objectives, the study examines digital quizzes in STEM higher education lectures. For this purpose, 8 digital quizzes in *genially* as well as 2 *Kahoot!* quizzes were created based on lecture materials for computer science students at the University of Applied Sciences Karlsruhe, Germany. The *genially* quizzes are designed as single player games, whereas the *Kahoot!* quizzes are to be played in pairs against each other in plenary sessions. These 10 games were incorporated into the curriculum over the course of 3 semesters. On average, one to two games were used per lecture.

To accompany the use of the games in teaching, an anonymous evaluation was carried out at the end of each semester. This approach is chosen to evaluate the digital quizzes in the computer science lectures in STEM higher education, allowing students to share their opinions and give feedback. The anonymous questionnaire allows students to reply honestly and openly in the feedback process without fearing judgement on their opinions. Therefore, questionnaires are suitable to gather data on perceptions, experiences, motivation, and attitudes towards these platforms (Manzano-León, Camacho-Lazarraga, Guerrero, et al., 2021). The use of surveys allows the participants to work through the questions at their own pace. Digital surveys underscore the advantage of self-determination and anonymity and is therefore often applied to educational settings (Reinders et al., 2022).

The questionnaire was designed based on the standard lecture evaluation at the University of Applied Sciences Karlsruhe, Germany. The survey included questions on students perception of digital serious games, based on relevant literature on game-based learning (Manzano-León, Camacho-Lazarraga, Guerrero-Puerta, et al., 2021). Ethical considerations, including informed consent and anonymity, were addressed to protect participants' rights and privacy. As the questionnaire was anonymous, no conclusions can be drawn about individual participants. A total of n=87 higher education computer science students participated in the study.

The survey comprised open-text fields, and the respective entries in the open-text fields were assessed employed qualitative content analysis according to Philipp Mayring (2015). Qualitative content analysis is applied to explore meanings and patterns in qualitative data (Mayring, 2015). A systematic approach with predefined rules ensures that the analysis is both reproducible and transparent, addressing scientific quality criteria. The main objective is the development of categories, following deduction or induction: Deduction is the application of pre-defined, theory-based category to the material, whereas induction is defined as observing patterns in the data without pre-defined categories (Reinders et al., 2022). Regardless of the chosen approach, qualitative content analysis can be conducted in three different ways: (1) summarizing the qualitative data by shortening the text; (2) explicating the data by enriching the text with more

data sources; or (3) structuring the material by units of meaning (Mayring, 2015).

In this study, the structured qualitative content analysis was employed. Following this approach, the participants' entries were analysed using thematic coding, providing a comprehensive understanding of the research subject. The findings are outlined in the following section.

Findings

The qualitative content analysis results in four main categories: *Pleasant atmosphere*, *Positive perception of digital serious games*, *Interactivity and engagement*, *and Diversification of lectures by using digital serious games*. The categories and the respective absolute as well as relative frequencies are displayed in the following Table 1.

Table 1. Qualitative Content Analysis Categories.

Category	Absolute frequencies	Relative frequencies
Pleasant atmosphere	3	3,6%
Positive perception of digital serious games	48	57,8%
Interactivity and engagement	25	30,2%
Diversification of lectures by using digital serious games	7	8,4%

Table 1 shows that most of the student responses can be categorized as positive properties of digital serious games. The majority of all entries can be classified under Positive perception of digital serious games. Student responses show that students generally favour digital game-based learning. Enthusiasm for educational games and positive responses to the adoption of novel teaching methodologies was captured. There is a notable appreciation for the replacement of conventional teaching methods.

In particular, students appreciate being incentivized to actively participate in lectures. This is represented by the category *Interactivity and engagement*, which accounts for 30% of the survey responses. The students value their active participation in the quizzes. Students emphasized that studying with digital serious games like quizzes helps them testing their knowledge. The digital serious games are appreciated for their student-centred design and intuitive usability.

The platforms *genially* and *Kahoot!* were assessed suitable for digital game-based learning by the students. Students enjoyed the digital learning games, especially the quiz characteristics were mentioned to be helpful for consolidating lecture content. The *Diversification of lectures by using digital games* comprises 8,4% of all survey entries. Students appreciate the incorporation of digital serious games, which is partly attributable to their computer science affinity. Consequently, it is not surprising that students did not have any issues with the game usability or navigation. Following, 3,4% of entries show that participants value the *Pleasant atmosphere* created by using digital serious games. Participants value the competitiveness of the quizzes in *Kahoot!* and mentioned positive effects on group dynamics when working in pairs. The integration of both genially and Kahoot! incentivized students to participate and actively engage in the learning activity. Traditional unidirectional teaching by the lecturer in which students are

passive shifted to the students actively by playing the games, adopting an active role in the learning process.

In addition to providing feedback, the participants suggested possible enhancements of digital serious games regarding their utilization, frequency, and design. The following recommendations for higher education lecturers are derived from this study:

- The education of digital educational games into higher education is recommended once or twice per lecture to consolidate previously acquired knowledge. The incorporation of gamified elements is imperative in the creation of competitive and motivating characteristics within the game.

- The challenge of digital games lies in the necessity to learn how to utilize the tools and invest time in creating and maintaining them. However, it should be noted that the functionality of these devices may be constrained when employed within the specific context of a given didactic application.

- Digital games have the capacity to stimulate learners' motivation by achieving an equilibrium between playful elements, competition, and enjoyment. Group competitions, in which all learners competed against each other, were found to be particularly appealing.

- It is important that these digital learning games are aligned with the learning objectives. These should be communicated transparently in advance, allowing students to allocate the digital serious game in their learning process.

Evaluating these findings, it can be stated that the game design needs to be student-centred and intuitive to minimize barriers and maximize student engagement. In addition, the content created on genially and the quizzes designed on Kahoot! is to be closely aligned with the learning objectives to minimize barriers for students to engage with the material, maximizing the educational impact.

Discussion

This study sheds light on how computer science students perceive digital serious games in a quiz-based format during lectures. Based on the underlying research question *How do computer science students perceive digital serious games in STEM higher education?*, this study shows that the participants are generally in favour of digital serious games. In brief, the participating students have indicated that the learning games were enjoyable and anticipate their incorporation into future curricula. Digital game-based learning platforms like *genially* and *Kahoot!* foster student engagement by addressing students' interest in playing games. Student motivation is addressed by the playfulness of the game, having a positive impact on student engagement and activation.

In addition to the positive experience with digital learning games, minor technical issues were observed within the scope of this study, such as network instability, which affected students experience with *Kahoot!*. These technical issues had a disruptive effect on the learning experience. Ensuring reliable internet connectivity is crucial for the seamless implementation of these platforms.

Moreover, it is worth mentioning that the time required to create interactive content on *genially*

and design quizzes on *Kahoot!* can be a challenge for educators, especially those with limited technological proficiency. Designing quiz-based digital serious games requires more resources than designing traditional unidirectional teaching materials. This aspect needs to be considered when deciding for game-based learning.

The qualitative analysis of participant feedback allowed to deeply examine the data. Nevertheless, it is recommended to further assess students' perception of digital serious games. It may be of interest to the research community to investigate which game design elements are particularly beneficial and which are rather harmful to learning environments. Targeting the challenge of students being easily distracted while learning, immersive game design elements could incentivize students to be more involved in digital serious games, therefore leading to less distraction. Therefore, immersive game design elements are recommended to be investigated in future research.

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Activating Epistemic Emotions To Enhance Student Engagement In Socio-Scientific Issues Through Digital Curation

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Learning through socio-scientific issues (SSI) confronts students with uncertainty, competing knowledge claims, and the need to justify positions in the absence of clear-cut answers. Such epistemically demanding learning situations are likely to evoke a range of emotions that are closely tied to students' processes of sense-making and participation in learning, yet these emotional dynamics remain underexplored, particularly in digitally mediated SSI contexts. Addressing this gap, the present study examined the potential of Digital Curation (DC) as a learning pathway for integrating SSI learning with intentional activation of epistemic emotions. The study employed a qualitative bounded case design in a tenth-grade biology classroom in Israel (n=42). Students participated in four structured units on animal welfare (food choices, environmental conservation, animal experimentation, and legislation). Data were collected through reflective written reports, semi-structured interviews, and video recordings of classroom discussions. A combined deductive–inductive content analysis was employed to investigate the interplay between epistemic emotions and dimensions of student engagement. The findings revealed that the SSI-DC learning pathway initially elicited negative epistemic emotions such as confusion, frustration, and anxiety, which gradually transformed into curiosity, enjoyment, and surprise as students progressed through the learning process. This emotional trajectory supported sustained engagement across cognitive, behavioural, emotional, social, and agentic dimensions. These findings underscore the importance of designing emotionally responsive digital learning environments that intentionally leverage epistemic emotions to enhance student engagement and foster a sense of ownership in learning.

Keywords: Socio-scientific issues, digital curation, epistemic emotions, student engagement

Introduction

In recent years, science education has shifted towards actively involving students in socio-scientific issues (SSIs) that directly connect to their everyday lives, rather than solely imparting scientific knowledge. This shift supports students' understanding of scientific concepts while encouraging critical examination, informed decision-making, and the construction of scientific arguments in response to ill-structured social dilemmas (Sadler et al., 2016). However, sustaining student engagement with SSIs remains challenging, particularly in digitally mediated learning environments (Klosterman et al., 2012; Solli, 2021).

Integrating Digital Curation (DC) into SSI teaching has recently attracted considerable attention due to its potential to enhance student engagement (Dayan & Tsybulsky, 2024). DC involves selecting, organizing, and preserving digital content to create coherent collections of relevant and reliable information (Tsybulsky, 2020) and has been shown to foster critical thinking and media literacy practices needed to navigate complex online information (Gadot & Tsybulsky, 2023; 2025; Forkosh et al., 2021).

Beyond its documented contribution to student engagement, integrating DC into SSI learning also places students in epistemically demanding situations that require them to search for information, evaluate the credibility of sources, negotiate conflicting claims, and justify knowledge-based positions. These features position DC not only as a pedagogical tool, but as a learning

environment that foregrounds processes of sensemaking under conditions of uncertainty.

Building on this perspective, our research group proposed the SSI-DC instructional pathway as a learning pathway within the SSI teaching and learning framework, integrating the social and scientific dimensions of SSI learning through digital curation (Dayan & Tsybulsky, 2024). In our prior SSI-DC work (Haj & Tsybulsky, under review), students frequently expressed confusion, curiosity, frustration, and surprise, suggesting that epistemic emotions - knowledge-focused emotions arising during information processing and sensemaking - may function as mechanisms that shape engagement (Brun et al., 2008; Pekrun & Stephens, 2012; Muis et al., 2018). Yet, research has rarely examined how epistemic emotions are activated in digitally mediated SSI contexts and how they contribute to multidimensional engagement (Fredricks et al., 2004; Sinatra et al., 2015). Accordingly, this study demonstrates how a designed SSI-DC pathway can transform negative epistemic emotions (confusion, frustration, anxiety) into positive ones (curiosity, enjoyment, surprise) and thereby strengthen cognitive, behavioural, emotional, social, and agentic engagement. The guiding research question was: How are epistemic emotions activated during the SSI-DC learning pathway, and how do they shape students' multidimensional engagement (cognitive, behavioural, emotional, social, and agentic)?

Method

Research Setting And Participants

This qualitative bounded case study was conducted in a secondary school in Israel and focused on a single tenth-grade biology classroom (n = 42). The classroom was selected as a bounded case (Yin, 2003), enabling an in-depth exploration of how the SSI-DC pathway influenced students' epistemic emotions and multidimensional engagement within their authentic instructional environment. The students were enrolled in an advanced science track and had prior exposure to SSI. Throughout the learning pathway, students participated in four structured SSI-DC units related to animal welfare (food choices, environmental conservation, animal experimentation, and legislation). Each unit spanned approximately 8 hours and required students to collaboratively research, curate, and reflect on digital content using Wakelet. Each unit began with an open-ended, provocative question, followed by whole-class discussion and peer dialogue in self-selected groups, and concluded with group presentations and whole-class evaluation of competing positions. All activities were conducted during regular classroom hours; units were required but ungraded. Ethical approvals were obtained from the Ministry of Education and the Institutional Review Board (IRB). Informed consent was obtained from all participating students and their parents, including permission for classroom video recordings. Confidentiality was ensured, and pseudonyms were used in all transcripts and reports.

Data Collection

Data were collected from three sources: (A) guided reflective written reports completed after each animal welfare lesson, focusing on students' emotional responses, engagement, and participation in the SSI-DC process; (B) face-to-face semi-structured student interviews conducted after completing the SSI-DC unit, including 14 open-ended questions examining students' emotions and perceptions of learning and engagement. Each interview lasted about 50 minutes, was recorded and transcribed, and remained flexible to follow participants' responses while prompting students to reconstruct the steps of creating their digital collections; and (C) video documentation of selected classroom sessions capturing group discussions, affective expressions, and collaborative reasoning, enabling analysis of verbal and non-verbal interaction and how epistemic emotions emerged and evolved in real time within the SSI-DC environment.

Data Analysis

We analysed the data using a combined deductive–inductive qualitative content analysis (Schreier, 2012; Kuckartz, 2016). Deductive coding was guided by established frameworks of student engagement (Fredricks et al., 2018; Sinatra et al., 2015) and epistemic emotions (Pekrun et al., 2016), while inductive coding enabled the identification of emergent patterns not captured by the predefined categories (Elo & Kyngäs, 2008). First, reflective reports, interview transcripts, and selected classroom video recordings were reviewed to familiarize ourselves with the data. Epistemic emotions were then coded using a theory-informed codebook developed based on Pekrun's conceptualization of epistemic emotions (Pekrun et al., 2016) and related empirical work on knowledge-related emotions in learning contexts. This codebook included definitions of each epistemic emotion (e.g., confusion, frustration, anxiety, curiosity, enjoyment, and surprise), their key features, and the cognitive conditions and triggers through which they typically emerge (e.g., contradictory information, uncertainty, difficulty verifying sources). In parallel, student engagement was coded using a multidimensional codebook grounded in established engagement models (Fredricks et al., 2018; Sinatra et al., 2015). This engagement codebook operationalized five dimensions—cognitive, behavioural, emotional, social, and agentic engagement—by specifying definitional characteristics and indicative manifestations in students' written reflections, interview responses, and classroom discourse. The data were subsequently revisited to examine how epistemic emotions co-occurred with, and shaped, students' engagement throughout the SSI-DC pathway, and themes were refined through iterative research team discussions.

Trustworthiness

To ensure trustworthiness, we applied triangulation across data sources—student reflections, interviews, and classroom observations—to enhance credibility (Lincoln & Guba, 1985). Multiple researchers independently coded the data and resolved discrepancies through discussion. The analytic process was systematically documented, and key interpretations were supported with direct excerpts from the data. Rich contextual information about the setting and participants was included to support transferability, while transparency in coding and decision-making strengthened confirmability (Shenton, 2004).

Findings

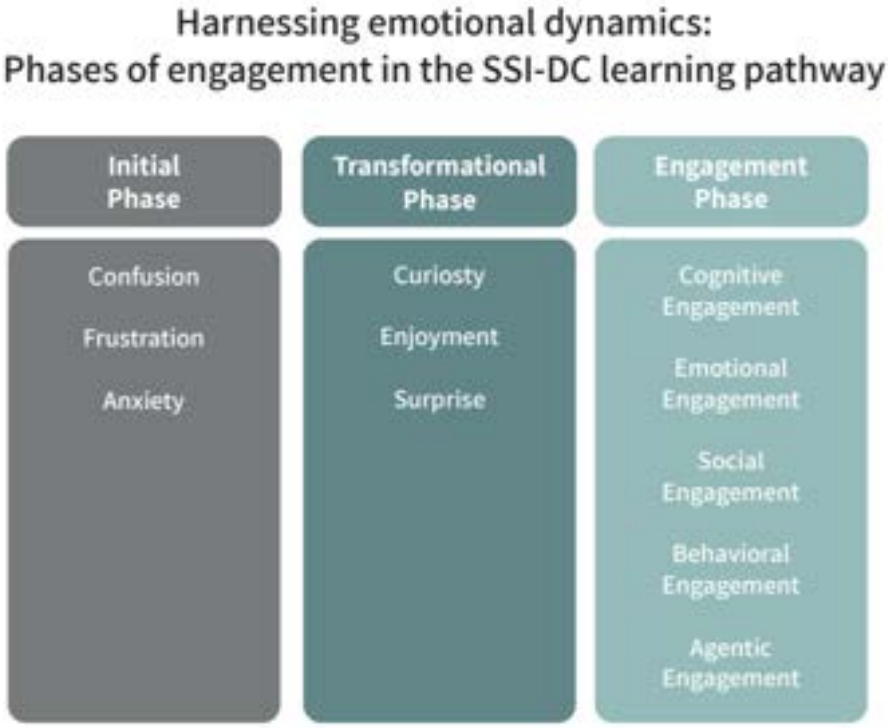
The findings presented in this section are organized into the Initial Phase, Transformational Phase, and Engagement Phase (see Figure 1). Each phase represents a different stage in the learning process and shows the dynamic interplay between the dimensions of engagement and the evolution of epistemic emotions in the SSI-DC learning pathway, thereby helping account for how engagement and epistemic emotions interact throughout the learning experience.

Initial Phase: Pre-SSI-DC Learning Epistemic Emotions

The initial phase reflects students' baseline epistemic emotions prior to engaging in SSI-DC. This stage was dominated by confusion, frustration, and anxiety, stemming from uncertainty about the unfamiliar learning method and the complexity of SSI tasks. Although these emotions were strongest at the outset, they occasionally reappeared later, especially when students confronted contradictory evidence or were required to justify their claims publicly. Positive emotions were limited during this phase and became more salient only in later stages.

A. Confusion: Introducing SSI-DC initially generated confusion, mainly due to unfamiliarity with the digital curation process and uncertainty about how to approach complex dilemmas.

Figure 1. The three phases highlight the dynamic interplay between the engagement dimensions and the evolving epistemic emotions in the SSI-DC learning pathway.



B. Frustration: Emerged when students struggled with information overload, unreliable sources, and disagreement within groups. In many cases, frustration also pushed students toward deeper searching and verification.

C. Anxiety: Was common as students worried about succeeding in an unfamiliar task and meeting expectations, especially under time pressure or peer comparison.

Table 1. Students' quotes illustrating epistemic emotions in the Initial Phase.

Emotion	**Students quotes**
Confusion	"At the start, I couldn't settle on a clear position, so I kept going back and forth and hesitated to speak." (DF10, interview) "I didn't understand how to approach the topic at first, and that uncertainty made me feel lost." (NF10, interview)
Frustration	"It frustrated me when others' views didn't align with mine, and it pushed me to search more intensely for supporting information." (DF10, interview) "There were so many sources, and many didn't seem reliable, which made the task feel overwhelming." (DF10, reflective report)
Anxiety	"At the beginning, I was worried and hesitant because the process was new and I wasn't sure I could handle it." (FF10, interview) "I felt anxious about not finding strong materials and not meeting expectations." (LF10, reflective report)

Transformational Phase: Transformation Of Emotions During SSI-DC

As students progressed through SSI-DC, the early negative emotions gradually decreased and were replaced by curiosity, enjoyment, and surprise. Although confusion and frustration occasionally resurfaced, they became less central. Positive epistemic emotions increasingly supported deeper inquiry, stronger collaboration, and more meaningful engagement.

A. Curiosity: Became a key driver of exploration and persistence, encouraging students to investigate multiple perspectives and verify information.

B. Enjoyment: Increased once students became comfortable with the platform and experienced successful collaboration and progress.

C. Surprise: Often appeared when students encountered unexpected insights or new arguments, prompting them to reconsider ideas and deepen reasoning.

Table 2. Students' quotes illustrating epistemic emotions in the Transformational Phase.

Emotion	Students quotes
Curiosity	"Exploring different sources and perspectives kept me engaged and made me want to continue investigating." (AF10, interview) "When I found evidence that challenged what I believed, I became more curious and checked additional sources to understand better." (JF10, classroom discussion)
Enjoyment	"Once I started working with different materials like videos, images, and articles, I felt increasingly excited." (FF10, reflective report) "I enjoyed building the digital collection and discussing it with the class—it made the learning feel engaging." (NF10, interview)
Surprise	"I was surprised by how much I learned and by how engaging the whole process turned out to be." (DF10, reflective report) "When another group presented evidence we hadn't considered, it surprised me and made us rethink our position." (HF10, classroom discussion)

Table 3. Students' quotes illustrating the five dimensions of engagement.

Engagement	Students quotes
Cognitive engagement	"Following the structured steps and building the group collection helped me understand the topic in a deeper way." (FF10, interview) "When classmates challenged my source, I rechecked it and justified it, which pushed me to analyse more carefully." (JF10, classroom discussion)
Emotional engagement	"As I learned more, the process became more enjoyable and broke the routine—it felt energizing." (KF10, interview) "Presenting our collection made me feel proud, especially because my contribution really mattered." (TF10, classroom discussion)
Social engagement	"Class discussions exposed me to ideas and information I hadn't encountered before." (DF10, reflective report) "Working together on the collection helped me understand more and made the learning experience more enjoyable." (KF10, interview)
Behavioural engagement	"I stayed highly involved and organized, completed all the steps, and even went beyond them because I wanted to keep researching." (DF10, interview) "Even when the group disagreed, I kept searching for evidence because I didn't want to give up." (LF10, classroom discussion)
Agentic engagement	"This approach made me feel like an independent researcher, responsible for building my understanding." (DF10, interview) "I suggested reorganizing our collection so it would be clearer, and once the group agreed, I felt my voice had real impact." (JF10, classroom discussion)

Engagement Phase: During SSI-DC Learning

In the engagement phase, curiosity, enjoyment, and surprise translated into sustained engagement across all five dimensions. Negative emotions appeared rarely and no longer shaped the overall

experience. Instead, positive epistemic emotions were the main drivers of students' effort, persistence, collaboration, and agency.

A. Cognitive Engagement: Students demonstrated deeper processing, synthesis, and critical evaluation of information as they built and defended their curated arguments.

B. Emotional Engagement: Was reflected in interest, enthusiasm, pride, and a growing sense of belonging during collaborative work and presentations.

C. Social Engagement: Peer dialogue and teamwork supported richer reasoning, exposure to new perspectives, and stronger learning relationships.

D. Behavioural Engagement: Students showed persistence, high effort, and increased time investment, even when facing disagreements or difficulties.

E. Agentic Engagement: Students increasingly shaped their learning by initiating ideas, personalizing tasks, and influencing group decisions.

Discussion and Conclusion

This study examined how epistemic emotions function as a mechanism for enhancing student engagement within the SSI-DC instructional pathway. Across the three phases (Initial, Transformational, Engagement), students shifted from negative epistemic emotions (confusion, frustration, anxiety) to positive ones (curiosity, enjoyment, surprise), and this trajectory supported sustained engagement across cognitive, behavioural, emotional, social, and agentic dimensions. These patterns align with research positioning SSI learning as engagement with ill-structured dilemmas that require learners to evaluate evidence, negotiate values, and construct arguments through discourse (Sadler, 2004; Zeidler, 2014; Sadler et al., 2017). They also reinforce the view that student engagement is multidimensional and dynamically shaped by instructional context (Fredricks et al., 2004; Sinatra et al., 2015). These phase-based patterns were identified through the theory-informed codebooks used in the analysis, which operationalized epistemic emotions and the five engagement dimensions across students' reflections, interviews, and classroom discourse (Pekrun et al., 2016; Fredricks et al., 2018; Sinatra et al., 2015).

The observed emotional transitions are consistent with theoretical accounts suggesting that epistemic emotions emerge when learners encounter uncertainty, contradiction, or cognitive incongruity in knowledge-rich tasks (Pekrun & Stephens, 2012; Muis et al., 2018; D'Mello & Graesser, 2012). Specifically, confusion and frustration appeared when students faced competing claims or struggled to verify sources, reflecting findings that epistemic emotions can be triggered by unresolved conflict and information overload in complex learning situations (Di Leo et al., 2019; D'Mello et al., 2014). Over time, these emotions shifted toward curiosity, enjoyment, and surprise—emotions that have been linked to sustained information exploration, deeper processing, and more productive engagement with knowledge-building tasks (Litman, 2008; Loewenstein, 1994; Brun et al., 2008). This progression supports Pekrun's control-value theory, which highlights how both negative and positive emotions can shape learning outcomes, but positive activating emotions are especially relevant for maintaining attention, persistence, and meaningful participation (Pekrun, 2006, 2016).

From a design perspective, three features of SSI-DC appear central to this transformation: (1) posing open-ended, controversial questions that create productive uncertainty and invite position-taking; (2) guiding students through iterative digital curation practices (locating, evaluating, organizing, and synthesizing resources) that surface contradictions and require justification; and (3) structuring collaborative dialogue and public sharing that prompts peer critique and refinement of claims. These design features resonate with research on technology-supported SSI

learning emphasizing digital practices such as evaluating sources, media literacy, and participation in discourse as core components of contemporary SSI pedagogy (Vlachopoulos & Makri, 2017; Solli, 2021; Soomro et al., 2020). They also align with digital curation literature positioning curation as an active knowledge-construction process that supports critical thinking, authenticity, and learner agency (Deschaine & Sharma, 2005; Pasek & Hargittai, 2015; Antonio & Tuffley, 2015).

The findings further showed that cognitive and emotional engagement were especially prominent, supporting prior work highlighting the interdependence of engagement dimensions and the central role of emotion in sustaining meaningful learning (Fredricks et al., 2016; Wang & Sui, 2020). Emotional engagement through curiosity and enjoyment appeared to stabilize students' persistence and investment in complex tasks, consistent with evidence linking positive affective experiences to academic engagement and success (Ucar & Sungur, 2017; Fredricks et al., 2016). At the same time, the collaborative structure supported social and agentic engagement, reflecting research emphasizing that peer dialogue and shared reasoning contribute to deeper engagement in SSI contexts (Sadler et al., 2017) and that agentic contributions are strengthened when students are positioned as active participants who shape their learning environment (Sinatra et al., 2015; Fredricks et al., 2018). Together, the phased model proposed here extends prior SSI-DC work by foregrounding epistemic emotions not only as outcomes of learning but as mechanisms that can be intentionally leveraged to strengthen multidimensional engagement in digitally mediated SSI instruction.

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A New Paradigm For Science Lesson Planning: Adaptive Expertise And Generative AI Integration

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This study examines pre-service teachers' reflections on using ChatGPT for lesson planning. As AI-integrated learning environments gain prominence in schools, preparing teachers for their future roles in science education is increasingly important. Building on Davis et al.'s (2024) emphasis on integrating AI tools in teacher preparation, we argue that using such tools is a critical practice for developing pre-service teachers' adaptive expertise. The data comprises 116 quotes from the reflexive writing of elementary pre-service teachers enrolled in science teaching methods courses during two semesters. Participants used ChatGPT as part of classroom activities to design 5E lesson plans. A coding scheme was developed based on two key dimensions of adaptive expertise—efficiency and innovation—and an additional category, collaboration, identified through open coding. Findings revealed that ChatGPT enhanced pre-service teachers' efficiency by streamlining the brainstorming process and generating lesson plan ideas quickly. It also supported their innovation by encouraging critical reflection and adaptation of ChatGPT's outputs to align with classroom contexts and student learning needs. Additionally, integrity emerged as an essential component of adaptive expertise in AI-integrated learning environments, highlighting the need for ethical awareness and critical evaluation of ChatGPT's relevance and accuracy. The study underscores the importance of repeated practice in using ChatGPT effectively and fostering critical thinking to ensure the appropriate adoption of AI tools in lesson planning. These findings offer valuable insights for practitioners and researchers aiming to prepare teachers for the challenges of 21st-century classrooms.
Keywords: AI literacy, Preservice teacher education, Qualitative research

Background

The use of AI tools, particularly ChatGPT, has grown substantially in education, with notable applications in teacher education programs. Goodman et al. (2024) highlighted the critical need to enhance pre-service science teachers' competence in effectively integrating ChatGPT to improve teaching practices and streamline lesson preparation. Furthermore, there is a growing demand for establishing ethical guidelines to ensure the responsible use of generative AI tools in teacher education, addressing concerns such as plagiarism and biases (University of South California, 2024, October 14). Despite these calls, clear strategies for supporting pre-service teachers in developing the competencies needed for lesson planning with generative AI tools remain lacking. Adaptive expertise, as emphasized by Hess et al. (2023), offers a comprehensive framework to address these challenges, balancing timesaving and creating a new idea. This framework not only helps preservice teachers to well prepare for the use of generative AI tools but also ensures that they critically evaluate AI outputs and adapt their practices to diverse and evolving educational contexts.

Adaptive expertise is the ability to flexibly navigate between routine efficiency and creative modification to solve problems (Opre, 2015; Schwartz et al., 2005). This competency is essential for managing the complexities of routine teaching tasks (Hess et al., 2023). Davis et al. (2024) highlight adaptive expertise as a foundational component in establishing teacher competencies for integrating generative AI tools into instructional development. Two key dimensions of adaptive expertise—efficiency (streamlining routine processes) and innovation (generating novel ideas)—are particularly relevant for effectively utilizing generative AI tools to create inclusive

science learning environments. For example, a 5th-grade science teacher might use ChatGPT to quickly generate ideas for inclusive activities related to a life science topic. The teacher can then critically reflect on these suggestions, assessing their understanding of inclusivity and adapting them to better meet students' needs. This iterative process of leveraging AI tools while engaging in reflective practice exemplifies the dynamic interplay between efficiency and innovation.

Building on the vital role of adaptive expertise in teaching, generative AI tools like ChatGPT significantly support teachers in exercising this competency, particularly in lesson planning. These tools enhance efficiency by enabling teachers to quickly access familiar information, such as the components of the 5E learning cycle (Engage, Explore, Explain, Elaborate, Evaluate), through simple prompts. In addition to this ability, teachers also need to be able to apply judgment and adapt AI-generated content to student needs, ensuring ethical use and addressing biases.

Theoretical Framework

Our framework emphasizes the interplay between adaptive expertise and the integration of AI tools in preservice teacher education, specifically within the context of science lesson planning. We identify three critical components essential for effectively leveraging adaptive expertise when utilizing generative AI tools in this context: efficiency, innovation, and integrity. Efficiency and Innovation represent the core dimensions of adaptive expertise**,** streamlining routine processes and fostering novel ideas. Building on this foundation, we introduce Integrity as an additional essential component. Integrity encompasses the ethical and reflexive application of AI tools, ensuring that their use aligns with educational goals and values while fostering trust in the learning process.

Efficiency refers to the ability to apply knowledge or generate solutions based on established routines quickly. According to De Arment et al. (2013), experienced teachers often exhibit high levels of efficiency in routine practices such as classroom management and lesson documentation. However, preservice teachers typically require additional support to develop efficiency, as they lack extensive experience in classroom teaching and interacting with students who have diverse needs.

Innovation, the second key component, is closely linked to flexibility—the ability to adjust context-specific decisions based on various students' learning needs. Unlike efficiency, which is rooted in routine and time-saving behaviours, innovation requires teachers to draw on their knowledge and skills to adapt prior experiences and make decisions that optimize student learning (De Arment et al., 2020). It involves grappling with complexity and finding ways to navigate and understand it within diverse classroom contexts.

The third component, Integrity, is particularly relevant in the context of generative AI tools. While efficiency and innovation enable effective decision-making, the integration of AI tools introduces the need for critical reflection on digital resources. Davis et al. (2024) emphasize that evaluating AI-generated content's reliability, bias, and ethical implications is a key competency in an AI-integrated educational landscape.

Balancing these three components**,** efficiency, innovation, and Integrity**,** is vital for leveraging generative AI tools effectively. Despite their importance, few studies have explored how adaptive expertise intersects with the use of generative AI tools in lesson planning. Our study aims to fill this gap by examining how these aspects contribute to teacher competency in AI-integrated environments.

Purpose of Study

The purpose of this study is to investigate how preservice teachers potentially demonstrate three key competencies—efficiency, innovation, and integrity—when using ChatGPT in science lesson

planning. Specifically, our research seeks to address the following questions:

1. To what extent do preservice teachers exhibit the three key competencies, efficiency, innovation, and integrity, when integrating ChatGPT into science lesson planning?
2. What common patterns emerge from preservice teachers' lived experiences with ChatGPT in the context of science lesson planning?

Method

Data was collected over two semesters, including the Spring and Fall semesters of 2024. Participants consisted of preservice elementary education students enrolled in elementary science teaching methods courses. As part of their coursework, students were required to design a 5E lesson plan to implement during their internships. To support this process, students were encouraged to use ChatGPT for brainstorming ideas, enhancing their ability to support diverse learners, and creating more inclusive learning environments.

Following the classroom activity, students submitted reflections as part of an exit task. These reflections were collected via a Google Form that included questions about the frequency of their ChatGPT usage, their preferences for using ChatGPT, and open-ended prompts about their overall experiences with the tool in lesson planning.

The data were analysed using a deductive qualitative analysis approach (Pandey, 2019). A coding scheme was developed based on the three key competencies for integrating generative AI tools in lesson planning, as outlined in the theoretical framework section (Table 1). Within these three broad categories, we developed specific codes by reviewing the data through several rounds of review.

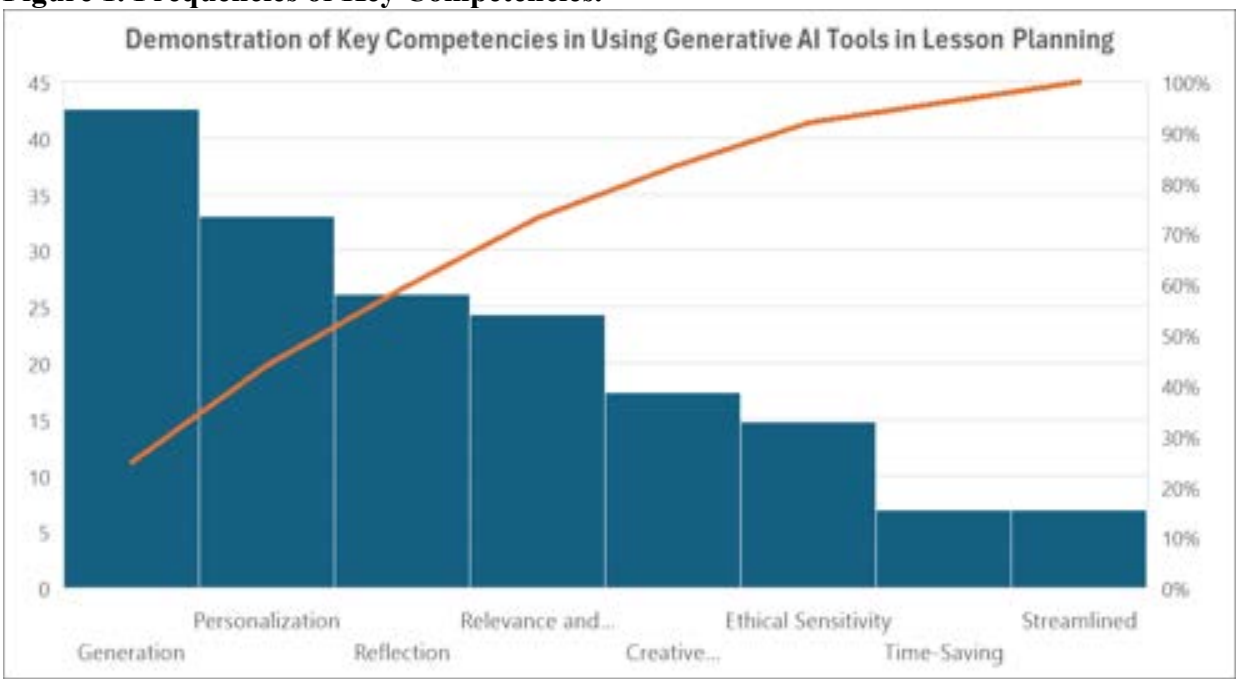
Table 1. Coding Scheme.

Category	Code	Explanation
Efficiency	Timesaving	AI reduces the time needed for lesson planning
	Streamlined Process	Preservice teachers easily adapt AI ideas to specific classroom needs.
	Facilitated Reflection	AI prompts deeper familiar tasks connecting new ideas with prior knowledge.
Innovation	Idea Generation	AI sparks strategies and ideas for science teaching as a brainstorming tool
	Creative Adaptation	Preservice teachers use AI outputs to develop various novel lesson plan ideas that suit their classrooms.
	Personalization for Equity	Preservice teachers recognize the necessity of tailoring AI suggestions to better meet diverse student needs and learning contexts.
Integrity	Relevance and Accuracy	Preservice teachers ensure AI outputs are relevant, accurate, and culturally sensitive.
	Ethical Sensitivity	Preservice teachers remain mindful of ethical concerns, including bias, and over-reliance on AI.

Findings

The data analysis allowed us to find answers to two research questions. First, we identified the competencies that participating preservice teachers demonstrated most frequently. Based on the analysis, participants showed a strong tendency toward idea generation, a component of the innovation category (Figure 1). Specifically, participants appreciated using generative AI tools to generate initial ideas for lesson design. This finding underscores a critical area for supporting preservice teachers in science lesson planning. De Arment et al. (2013) emphasized that unlike experienced in-service teachers, preservice teachers often require additional scaffolding to bridge their theoretical understanding from teacher education courses to practical applications in real classroom environments. Our study highlights the importance of fostering innovation through generative AI tools, demonstrating their potential to enhance preservice teacher education.

Figure 1. Frequencies of Key Competencies.



Additionally, the findings revealed that participants exhibited a high sensitivity to the integrity aspect. While they found generative AI tools helpful for creative brainstorming and starting lesson plans, they also expressed awareness of ethical considerations and potential biases inherent in using such tools. This aligns with Davis et al. (2024), who stress that integrity is a critical competency in the emerging era of generative AI in education.

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Our findings are consistent with existing literature that emphasizes the importance of integrating AI tools into science teacher education. However, this study advances the conversation by focusing on three critical competencies, efficiency, innovation, and integrity, necessary for the effective and responsible use of generative AI tools. These findings have important implications for science teacher educators, suggesting the need for the intentional incorporation of generative AI tools into teacher preparation programs to foster adaptive expertise while addressing both opportunities and challenges.

Conclusion

This study demonstrates how ChatGPT into science lesson planning is not merely about AI proficiency but about fostering adaptive expertise. Our findings highlight a critical shift in teacher preparation: while ChatGPT significantly enhances efficiency by streamlining the brainstorming process for science lesson planning, its true value lies in its role as a catalyst for innovation and integrity. By engaging in interactive prompting, pre-service teachers moved beyond passive adoption of AI generated content. Instead, they practiced critical reflection, adjusting AI suggestions to better cater to diverse learning needs and promote effective science learning environments. This process of innovative planning with AI underscores the necessity of high-level teacher agency. While AI helps brainstorm, the pre-service teachers develop their lesson plan ideas based on the context of classroom learning environments.

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Conception Of Inclusive Learning Environments Related To Biodiversity And Geodiversity: An Innovative Project For Pre-Service Teachers

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Young people's contact with nature has been decreasing, leading to negative consequences for their physical and psychological well-being. Additionally, education faces the challenge of including all students in the learning process, regardless of their functional, social, linguistic, or cultural characteristics. This project aimed to address these issues and involved 36 primary pre-service teachers in the development of inclusive educational resources focused on areas rich in biodiversity and geodiversity, while also integrating mother tongue content. The participants received scientific and didactic training to design more inclusive digital resources. The evaluation of these resources was based on indicators aligned with recommended principles. On a positive note, the pre-service teachers managed to explore biodiversity, geodiversity, and mother tongue learning in an integrated manner. However, they faced challenges in formulating coherent questions—both closed and open—and in simplifying scientific concepts. The resources were deemed adequate in aspects such as font type, size, and spacing, but the choice of colours often failed to follow inclusive criteria, being more driven by aesthetic preferences. Although the resources included audio texts, the diction was sometimes unsuitable for students with Portuguese as a non-native language. As a result, characteristics such as flexibility, simplicity, and equitable use were only partially achieved. The most promising resources will be tested with state school students later this school year, allowing for further adjustments before being made openly available on the website of the institution responsible for the project.

Keywords: Inclusive Learning, Digital Resources, Biodiversity and Geodiversity.

Introduction

The contact of young people with nature has been declining over recent decades (Freeman & Quigg, 2009; Woolley & Griffin, 2015; Almeida, Rato, & Dabaja, 2023). The consequences of this decline are significant, as such contact contributes to children's mental and physical health, stimulates the development of their cognitive, social, and emotional skills (Frost, Wortham, & Reifel, 2012). Furthermore, this lack of contact appears to reduce knowledge about native biodiversity, affecting not only children but also teachers in training (Almeida, García Fernández, & Strecht-Ribeiro, 2019). Louv (2010) even states that we are experiencing a deficit in nature contact and that the widespread use of the internet and electronic devices has also contributed to this situation.

Nevertheless, technologies are increasingly present in people's daily lives. Their utility and necessity in various contexts have grown, making it impossible for schools to ignore them. Technologies offer an ever-expanding range of applications, and many educational resources are in digital format. As Almenara and Ruiz-Palmero (2018) quote, Information and Communication Technologies (ICT) are one of the key variables in the knowledge society. Whether we are for or against it, the world in which we operate is increasingly technological and will continue to be so,

making their inclusion in schools, and consequently in teaching and learning processes, inevitable.

Education is also currently faced with the challenge of including all students in the learning process, regardless of their functional, social, linguistic, or cultural characteristics. In Portugal, the legal framework for inclusive education (Decreto-Lei n.º 54/2018) assumes that all students have the right to fully participate in a common educational project and to benefit from support that meets their needs, potential, and expectations. So, students from diverse social backgrounds, and a growing number of children from countries where the Portuguese language is not the official language, highlighting the multicultural reality of regular schools nowadays. The decree embodies a vision of inclusive education aligned with Universal Design for Learning (UDL) principles, which provide a framework that can be used to proactively design inclusive, flexible, and welcoming learning environments, considering the variability of all students (Rose & Meyer, 2006). The UDL stands at the forefront of contemporary efforts to create universal access to educational curricula for all students, including those with disabilities. Thus, the need to design more inclusive resources using digital tools aligns with UNESCO's (2009) recommendation of "education for all," as well-designed digital resources can better reach students with diverse characteristics.

The European Agency for Special Needs and Inclusive Education (2015) also emphasizes the fundamental role of inclusive practices in promoting equitable educational opportunities. Similarly, the Sustainable Development Goals (SDGs), specifically Goal 4 (Quality Education) and Goal 10 (Reduced Inequalities), underline the importance of these practices. However, such practices still lack the necessary prominence (Stinken-Rösner et al., 2020), with these authors pointing to a significant gap in research and practice in this critical area.

In this context, the present project aims to contribute to addressing the identified gap and fostering inclusive educational practices.

The Project

The present project, with the acronym GreenLink, aimed to address the various challenges outlined earlier. On one hand, it seeks to promote contact with biodiversity and geodiversity, thereby increasing knowledge and interest in nature. On the other hand, it aims to foster this contact through inclusive digital resources, supporting the inclusion of students from diverse backgrounds.

The project is focused on enhancing the training of pre-service teachers by deepening their scientific knowledge of biodiversity and geodiversity, as well as their pedagogical knowledge for designing inclusive digital resources for primary education. This involved applying knowledge acquired through outdoor activities.

At this stage of the project, during which the resources were designed, the goal is to highlight the challenges faced by the pre-service teachers in creating these resources after their training. Based on this evaluation, the resources have since been improved, and their testing with primary school children is scheduled to take place during the current academic year. The goal is to make these resources available on the institution's website, which offers a range of open-access digital resources for teachers.

Figure 1. The webpage of Lisbon School of Education where the resources will be available.



Methodology

The project involved 36 (35 females) primary pre-service teachers enrolled in two master's courses, with a mean age of 23 (SD=2.013), and four higher education professors. The project was developed across two curricular units: one scientific, Earth Science, focused on biodiversity and geodiversity knowledge, which included outdoor activities in nature; and another didactic unit called Integration Projects: Mother Tongue-Science. The latter explored integrative themes between language and science, emphasizing different text types, metaphorical and analogical language, argumentation on socioscientific topics, and children's literature. Additionally, it highlighted principles to follow in constructing assessment items and designing more inclusive digital resources, elements that were evaluated in the resources created. Pre-service teachers were tasked with designing an interdisciplinary inclusive resource for children, focused on the educational exploration of natural sites visited during the Earth Science curricular unit.

In preparing the pre-service teachers, emphasis was placed on the seven principles defined by Santos and Fernandes (2017) for designing inclusive resources: (i) equitable use, which refers to the resource being usable by everyone, regardless of their skills; (ii) design flexibility, which ensures accommodation of diverse user preferences and individual capabilities; (iii) simple and intuitive use, which highlights the resource's functional aspects; (iv) perceptible information, adapted to users' sensory needs, whether visual, auditory, or linguistic; (v) error tolerance, addressing potential negative consequences resulting from unintentional actions during use; (vi) low physical effort, ensuring the resource does not cause user fatigue; (vii) size and space for approach and use, designed to meet accessibility and manipulation requirements, considering factors such as posture, height, or mobility.

The pre-service teachers' training also incorporated principles outlined by the Centre on Inclusive Software for Learning (CISL, n.d.), such as line and letter spacing, font size, and type. It is widely agreed that greater spacing facilitates reading, especially for children and individuals with dyslexia. Additionally, larger font sizes improve comprehension and reading fluency for individuals with dyslexia and benefit those with visual impairments. Optimal font sizes vary across studies, ranging between 18 and 26, while simpler fonts like Arial or Verdana are considered more effective.

The choice of colours for resources also requires careful consideration to combine background and text/image colours that are complementary. These contrast patterns result in more efficient and comfortable visual performance, particularly for individuals with visual impairments or dyslexia.

Eight resources were developed in groups using Genially software. Group working was supported through tutorials, which allowed for iterative improvements to the resources. After their conclusion, each project was graded as part of the assessment of the curricular unit with didactic content. The marks given were based on an analysis grid, which included indicators reflecting the principles of inclusive digital resource design. Both positive aspects and persistent shortcomings were noted, even after the tutorials. Testing with primary school students, planned for the current academic year, will further evaluate and refine each resource.

Results

The resources were focused on several of the sites visited during the outdoor activities, with three being the most frequently chosen. This preference may be attributed to their potential for linking geodiversity and biodiversity and the presence of legends associated with two of them. These legends were seen by the pre-service teachers as a great possibility to integrate mother tongue and science, leading them to explore the natural features of these sites alongside the legends they inspired.

Other language-related contents incorporated into the resources included various text types (informative, narrative), word families, and derivation through prefixation and suffixation, integrated with multiple scientific concepts.

The construction of resource items, despite improvements during the tutorial sessions, posed challenges on several levels. Due to their lack of professional experience, pre-service teachers struggled to use simple language when defining scientific concepts. Difficulties were also identified in the formulation of open questions, which were often overly complex. In other resources, common errors in multiple-choice items included options with significantly unequal lengths and inconsistent grammatical constructions.

The selection of images was a positive aspect, as pre-service teachers had taken many photos and created short videos during the outdoor activities. Additionally, the use of artificial intelligence-generated imagery as a complement to their photos was a common practice among most groups and proved to be successful.

Regarding the seven principles to be considered in the development of digital resources, equitable use, flexibility of use, and simple and intuitive use were partially achieved. In fact, linguistic complexity, the failure to include audio instructions in several cases, poor diction in reading some texts, and the lack of instructions on how to approach certain tasks were evident in almost all resources, although in most cases these problems were found in only parts of the resources. Consequently, the information was not always easily presented for those with auditory or linguistic difficulties.

On a more positive note, the resources ensured that only a few negative consequences occurred to the users when moving forward in a resource, and the instructions, when present, did not require extra effort from the user.

Among other positive aspects, the font type and size chosen in most cases were effective. However, the selection of colours was somewhat neglected in terms of ensuring sufficient contrast, which is crucial for inclusivity. The pre-service teachers seemed to prioritize aesthetic preferences over the needs of all users.

Discussion and Conclusions

From the analysis conducted, it can be concluded that the design of inclusive digital resources is not an easy task and that the possibility of reaching all students is a difficult goal to achieve.

Nevertheless, the training provided allowed pre-service teachers to consider aspects that made the resources more inclusive, although others were overlooked. The attempt to reach students whose first language is not Portuguese proved to be partially successful, as better diction in reading contents revealed a need for improvement. The tendency to approach scientific concepts in a more complex manner also resulted, in part, from the scientific preparation that the pre-service teachers had been undergoing and their difficulty in finding simpler ways to explore these same concepts now for a younger audience. The exploration of biodiversity and geodiversity in an articulated manner proved to be more successful, perhaps because the course they had been attending sought this same articulation. The connection between science content and mother tongue content was also generally successful, with pre-service teachers showing some creativity in the selected articulations. As mentioned, the resources will only be freely accessible after being tested with students from state schools with diverse characteristics. However, the option to access the resources via provided links or QR codes already allows for an initial assessment of their potential and limitations.

Moreover, the process highlighted the importance of ongoing reflection and feedback when designing inclusive resources, emphasizing that initial attempts often need substantial refinement. Observing how different students interact with the materials will provide critical insights into the adaptability and accessibility of the resources. Future revisions are likely to benefit from closer collaboration with experts in language acquisition and special education, helping to address any remaining gaps more effectively. Ultimately, this experience underscores that inclusivity in educational resource design is an iterative process, requiring patience, continuous learning, and a willingness to adjust strategies based on real-world classroom experiences.

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Bridging Digital And Physical Worlds: Leveraging AR And AI For Personalized Science Education In Geography And Astronomy

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This article presents a Preliminary Design Report (PDR) of the prototype of the educational game AcademIa of ARistarchus, which integrates Augmented Reality (AR) and Artificial Intelligence (AI) to revolutionize science education. By addressing persistent challenges such as student misconceptions, the game focuses on enhancing the understanding of complex concepts in geography and astronomy. In an era of rapid technological advancement and increasing environmental concerns, this game aims to prepare students for future challenges. AR allows students to interact with and visualize abstract scientific phenomena, including the greenhouse effect and planetary atmospheres, while AI provides personalized learning experiences by offering real-time feedback. Guided by established learning theories, the game intends to promote critical thinking, problem-solving, and collaboration among students. By providing a technology-enhanced model for science education, AcademIa of ARistarchus lays the foundation for future innovations in educational technology.

Keywords: Augmented Reality, Artificial Intelligence, Science Education

Introduction

The integration of technology into education is vital in today's rapidly evolving digital landscape. Emerging technologies such as AR and AI have shown immense potential for transforming how students engage with complex scientific concepts. In response to the conference theme of transitions and transformations in education, this research explores the design of *AcademIa of ARistarchus*, a prototype that aims to enhance student comprehension of geography and astronomy through innovative digital tools.

A detailed literature review of AR and AI-based educational applications revealed a gap in integrated solutions for these disciplines (Georgiou et al., 2024; Georgiou et al., 2025). While AR enhances understanding by visualizing abstract concepts (Yen et al., 2013), AI provides personalized learning pathways through adaptive feedback (Ayeni et al., 2024). Despite their potential, few initiatives effectively combine these technologies to create immersive educational tools. Addressing this gap is essential for making science education accessible and engaging.

The design of the prototype AcademIa of ARistarchus aims to fill this gap by engaging students in immersive scenarios that explore the greenhouse effect on Earth, Mars and Venus, the planets' atmospheres and the role of human activities in Earth's greenhouse effect. The final purpose is to develop an educational game to address research questions, such as whether it enhances students' knowledge about geography and astronomy topics such as the greenhouse effect and planetary atmospheres.

Prototype Design Framework

Core Idea And Purpose

The core idea of the AcademIa of ARistarchus is to develop an engaging and educational game centred on planetary atmospheres and the greenhouse effect. The game will integrate modern technological tools, such as AR and AI, to enhance the learning experience. Designed for students

aged 10 to 12, it aims to be both educational and enjoyable. Subsequently, the educational aspects of the game as well as the gameplay features are illustrated.

Learning Objectives And Learning Theories Used In The Design

Learning Objectives

The prototype's learning objectives are designed in alignment with Bloom's Taxonomy (Krathwohl, 2002). Additionally, relevant goals from the Greek Geography curriculum have been incorporated. The knowledge objectives of the game, are organized into three thematic units, each with corresponding learning outcomes, as described following:

Thematic_Unit_1: The atmosphere composition of Earth, Mars, and Venus. Students will be able to:

- Define the atmosphere.
- Compare the atmospheres of Earth, Mars, and Venus.

Thematic_Unit_2: The greenhouse effect on these planets and its role in regulating planetary temperatures. Students will be able to:

- Define the greenhouse effect.
- Justify why Venus has higher temperatures compared to Earth and Mars.
- Explain the greenhouse effect and the role of greenhouse gases in increasing planetary temperatures.
- Compare the temperatures of Earth, Mars, and Venus.

Thematic_Unit_3: The impact of human activity on the greenhouse effect. Students will be able to:

- Describe how human activities influence the greenhouse effect.
- Categorize the human activities that intensify the greenhouse effect.
- Propose solutions to mitigate the impact of human activities on the environment.
- Evaluate whether human activities are the primary cause of the increase in Earth's temperature.
- Critically assess which solutions are most effective in reducing CO_2 emissions.

The prototype also aims to develop collaboration and communication skills through teamwork and problem-solving.

Learning Theories

In AcademIa of ARistarchus, several learning theories were integrated into the prototype design to enhance student engagement, described as following:

- Constructivism: Players build knowledge by solving interactive problems, experimenting with scientific scenarios, and utilizing AR/AI features to enhance their understanding of key scientific concepts.
- Behaviourism: Players receive rewards for their actions, promoting motivation and reinforcing positive behaviour in learning.
- Active Learning: The prototype fosters hands-on engagement through problem-solving, requiring players to make decisions.

- Social Learning: Group tasks and teamwork allow players to share strategies and learn collaboratively, enhancing group dynamics.
- Multidimensional Learning: The use of AR/AI offers diverse perspectives and learning styles, enriching the educational experience.

Gameplay Features

Prototype Scenario

The story of AcademIa of ARistarchus takes place in the future, where the effects of rising temperatures are still undeniable. The players take on the role of aspiring scientists tasked with developing strategies to protect the planet's future. To accomplish this, they have to explore the greenhouse effects and planetary atmospheres of Mars and Venus and participate in activities to propose solutions to mitigate the impact of human activities on Earth's atmosphere. The players' objective is to answer questions accurately and successfully complete activities, earning stamps for their pAsspoRt and collecting tokens as they progress. The winner is the player who has collected all the stamps in the pAsspoRt and has gathered the most tokens.

Gameplay Mechanics

Drawing from principles of immersive learning and serious gaming (Bopp, 2008; Wang & Huang, 2021), the design of the prototype combines clear educational objectives, real-world challenges, compelling storytelling, interactive gameplay, and effective reward systems to create a meaningful and engaging experience for players. More specifically, the gameplay mechanics implemented are the following:

- Starting Point: Players embark on their journey from the island of Samos, Greece, equipped with a grant of tokens from the Cosmos Exploration Institute. They are supported by Aristarchus, an AI assistant tutor, which will help them overcome challenges along the way. Movement across the game board is determined by a micro:bit dice roll, allowing players to advance 0 to 3 steps. This adds an element of excitement to the journey.
- Interactive Challenges:

(a) The Cosmos Library offers three types of cards: Action_Cards, Exploration_Cards, and AR_Cards. As players progress, they draw cards, each presenting unique, time-bound challenges designed to test their knowledge and critical thinking skills. Action_Cards present collaborative challenges where players have to team up to solve critical questions and activities. Exploration_Cards focus on key scientific topics like the greenhouse effect and human impact on the environment, offering both knowledge-based and thought-provoking challenges. AR_Cards introduce interactive experiences through QR codes. For example, players will have to adjust greenhouse gas levels and observe how these changes alter global temperatures and the greenhouse effect. These cards offer an immersive and hands-on learning experience.

(b) Along the way, players must also overcome obstacles like solar storms, which adds complexity to their journey by disrupting their progress.

- Motivational Rewards: These tokens (RFID cards) are crucial for progressing and unlocking additional challenges. There are several parts in the game where players gain tokens. Firstly, they earn tokens from the Cosmos Exploration Institute for successfully completing missions. In addition, Action_Cards reward players when collaborating effectively in solving critical questions and activities. Moreover, the Exploration_Cards'

varying difficulty levels provide corresponding tokens. The token-based reward system motivates players to engage deeply with the content, encouraging both learning and progress throughout the game.

- Checkpoints: Key locations on Earth, such as the Arctic, which are highly connected to impacts of human activities, serve as checkpoints where players interact with AR_cards to explore the atmosphere, the greenhouse effect, and the impacts of human activities on these phenomena. Each checkpoint visit is marked with a stamp in the player's pAsspoRt.
- Equipment for Space Missions: layers who invest in higher-tier equipment will gain a strategic advantage in completing challenges and activities, allowing them to solve questions and tasks more thoroughly.
- Winner: Upon completing all tasks, players return back to Samos. The player who successfully finishes the journey and collects every stamp in the pAsspoRt will be ranked on the leaderboard according to the number of tokens earned. Subsequently, the top player will be crowned the winner.

Design Model Of The Prototype

- The game board features an illustrated Global Map of the Earth at its centre with Mars and Venus positioned on opposite sides, symbolizing interplanetary exploration. Players traverse paths across Earth's diverse regions, leading to the other planets for space missions.

The design of the prototype follows a hybrid approach, combining the waterfall model (Ruparelia, 2010) for the initial requirements specification and prototype design, with the agile methodology, as outlined by Al-Azawi et al. (2014), for iterative development and continuous refinement. The initial phase involved specifying the requirements and designing the prototype to ensure alignment with the learning objectives described in the previous section. Subsequently, iterative development cycles were applied, incorporating expert review and theoretical refinement at each stage. This approach, consistent with Agile principles, allows continuous refinement and improvement of the prototype's design.

Methodology for Future Work

The future work for AcademIa of ARistarchus involves several key steps: iterative development cycles were applied, incorporating expert review and theoretical refinement at each stage. This report serves as the Preliminary Design Report of the project. Final development will integrate feedback to refine and expand the game, ensuring it meets quality standards before full-scale implementation.

The evaluation process will involve a mixed-methods approach to collect both quantitative and qualitative data. A sample of 120 students aged 10-12 from different schools will participate in the study. The game's effectiveness will be measured using pre- and post-tests to assess knowledge acquisition, Likert-scale questionnaires to gauge engagement and enjoyment, and semi-structured interviews to gain deeper insights into student experiences. A triangulation approach will enhance validity and reliability by cross-referencing questionnaires, observations, and interviews. Quantitative data will be analysed statistically using t-tests to compare mean scores, while qualitative data will be thematically coded to identify recurring patterns and insights.

The study, scheduled for September 2025, aims to evaluate how the AR/AI game enhances students' understanding of the greenhouse effect and planetary atmospheres. Findings will guide

future improvements to optimize the game's learning potential and user experience.

Discussion

Integrating AR and AI in education enhances students' understanding of complex concepts through interactive learning. However, challenges such as technological complexity, accessibility, and equipment requirements must be addressed. Some key questions to consider are as follows: What are the pros and cons of AR/AI in teaching? How can these technologies be optimized for better learning outcomes? What challenges emerge when teaching complex scientific concepts/phenomena? How could the game be adapted to different age groups?

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Talking To Or Talking Through Teachers - An Analysis Of A Digital Teacher's Guide

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Teaching materials not only support students but also support teachers in how they transfer their subject knowledge to teaching. Teacher guides are often digital and can address teachers by talking through or talking to the teacher, thus supporting teachers. In this paper a digital teacher's guide for grades 7-9 is analysed to see how it communicates with the teachers. The teacher's guide in technology education was analysed by content analysis in two steps. Firstly, on whether it talks to the teacher or through the teacher, and secondly the units that talk to the teacher were analysed by using six design principles. The results show that most of the guide (75 %) is text that talks through the teacher, e.g. by giving direct instructions for the teacher on how to carry out the teaching. In the remaining sections of the guide, text that talks to the teacher, there are examples of all six design principles. These sections include the purpose and structure of each chapter, describe key content, highlight challenges, suggest teaching adaptations and provide definitions of important terms and concepts. The analysed guide does not take advantage of the benefits of digitalization. Teacher guides should enable teachers to adapt and expand upon the material. It is important to design teacher guides with more text that speaks to teachers, not just through them.

Keywords: Teaching materials, K-12 Education, STEM education

Introduction

Teaching materials, such as textbooks and teacher guides, play a central role in the way teachers transfer their subject knowledge into teaching. Teaching materials support teachers and influence the choices they make in planning and delivering lessons (Oates, 2014). Teachers with low subject knowledge are particularly dependent on teaching materials. Teacher guides in particular have the potential to support teachers in different ways.

Teacher guides are often digital. The digital format provides the possibility to redesign the material, i.e. to do what was not possible with the analogue format (Puentedura, 2020; Blundell et al., 2022). Remillard (2000) distinguishes between how the teacher guides communicate with teachers. Teacher guides that talk through the teacher and tell the teacher what to do, while teacher guides that talk to the teacher explain the underlying ideas of these suggestions.

In this paper, we analyse a digital teacher's guide for grades 7-9. The purpose is to give an account of the ways in which the examined teacher's guide communicates with the teachers, in terms of talking through and talking to the teacher.

Theoretical perspectives

Educative Curriculum Materials

Remillard (2000) points out that teacher guides commonly talk through teachers but argues that they should be designed to speak to teachers. However, van Steenbrugge and Ryve (2018) emphasise that teacher guides that talk through teachers can also be a support, especially for teachers who feel insecure about the subject or are unaccustomed to teaching situations.

Distinctive for educative curriculum materials (talk to teachers) is that they include educative features specifically designed to support teachers when adapting their teaching, both regarding content and how to conduct teaching. Based on Davis and Kracjik's (2005) guidelines for how and why teacher guides should be designed, and studies where versions of these guidelines were tested (Arias et al., 2016; Davis et al., 2014), Davis et al. (2017) constructed six design principles to characterise teacher guides in science education. These can shortly be described as:

1. Educative features should suggest ways to adapt lessons without losing their purpose.
2. Educative features should explain the reasoning behind pedagogical ideas and support teachers in adopting these ideas through contextualised examples.
3. Educative features should help make important content visible and explain it, showing how it connects across lessons.
4. Educative materials should offer various types of features to meet diverse needs.

Principles 5-6 are excluded since they are not used in this study.

The SAMR-Model

The SAMR-model (Substitution, Augmentation, Modification, Redefinition) is a model for integrating digital technology in education. Puentedura (2009) describes it as a guide for how teachers can design tasks and learning processes when using digital technology in education and states that digital tools can either be used to improve existing analogue teaching practices or to fundamentally transform them to a digital format. He describes four levels of integration:

- Substitution: at this level, the digital format is simply replacing the analogue format and offers no improvement or functional change.
- Augmentation: existing practice is improved by the digital tool.
- Modification: Instead of teaching in the same way and using the same tasks, the digital tool is used to adapt and change the tasks.
- Redefinition: The digital technology allows for and is used to create new tasks, and is transforming learning.

Learning activities categorised as substitution or augmentation are understood to improve or support learning, whereas those categorised as modification or redefinition are considered to fundamentally transform the learning experience (Romrell et al., 2014, with reference to Puentedura).

Since we study teacher's guides as potentially educative for teachers, we find the SAMR-model useful for analysing how the design of the teacher's guide benefits from the digital format in order to enhance teachers' understanding of how to organise and enact the teaching.

Method

The Teacher's Guide

The teacher's guide of a widely used curriculum material for technology education in grades 7-9 in Sweden is analysed (Lovén & Citrohn, 2022). It is a digital resource and can be bought as a complement to the textbook. Its size is equivalent to about 200 pages in book form, consisting of an introduction and six chapters based on the same structure. First, introduction, connections to the curriculum, and assessment. This is followed by sub-chapters corresponding to the textbook, covering the content (facts and theoretical information) and projects (tasks and assignments) contained in the book.

Analysis

To study how the teacher's guide benefits from the digital format, we looked at all the features of the digital guide and categorised them according to the four levels of the SAMR-model.

To examine how the teacher's guide communicates with the teacher, content analysis was performed in two steps. First, we coded each unit (phrase, sentence or paragraph) based on whether it talks *to* the teacher or *through* the teacher (Remillard, 2000). Then, we further coded the units that talk *to* the teacher using an adapted version of the design principles created by Davis and colleagues (2017). We used the original design principles 1-4 but modified 5-6 to fit the technology subject, inspired by Robert's vision I and II: like other researchers in technology education (e.g. Stoor & Popov, 2021).

1. In technology education, students should try, analyse, and evaluate working methods in various technical areas, such as design processes and life cycle analyses. The teacher's guide should provide examples of how work in different technical disciplines is carried out in practice and how this can be part of the teaching.
2. One objective for technology education is to prepare students to become conscious citizens in a society where technology plays a central role. The teacher's guide must support teachers in motivating the importance of technology education for society and everyday life and provide examples that highlight technical knowledge for making decisions at both individual and societal levels.

All three researchers coded the first chapter of the teacher's guide individually and subsequently discussed the coding agreement until consensus. The remaining chapters were divided among the researchers.

Findings

First, we present the findings related to the digital format of the teacher's guide. Second, the findings are summarised based on whether the text talks *through* or talks *to* the teacher.

The Digital Format Of The Teacher's Guide

This teacher's guide is digital, but it resembles a printed version. It does not offer any additional functionality compared to what an analogue guide can do. Thus, it is a substitute for a printed guide and placed at the substitution level in the SAMR-model.

Text That Talks *Through* The Teacher

Approximately 75% of the teacher's guide is text that talks *through* the teacher, where a large part is the answers to the questions in the textbook. Also, there are direct instructions for the teacher on how to perform the teaching. These are clear and explicit: *Let the students read the text on pages 48–55 silently or read the text aloud to them* or *Use the worksheet and have students write a list of various technical solutions*.

Overall, most of the guide talks directly *through* the teacher, who can essentially use it as a script. Alternatively, it can be employed as a practical step-by-step guide: *Distribute the worksheet to the students, then ask them to answer the questions*.

Text That Talks *To* The Teacher

The teacher's guide contains about 25 % text that talks *to* the teacher, mainly in the Introduction sections. These sections outline the purpose and structure of each chapter, describe key content, highlight challenges, suggest teaching adaptations and provide definitions of important terms and concepts. Additionally, the guide connects the content to the syllabus of technology education.

Another part of the teacher's guide where there is text that talks *to* the teacher is in the Assessment sections. These sections include a rubric providing examples of student responses at passing level and at higher grade levels. Findings and examples from each principle are presented in Table 1.

Table 1. Design principles 1 to 6 with examples.

Design principle (DP)	Findings	Example
DP1 – suggestions on how lessons can be adapted in several ways without losing the intended purpose.	Not extensively covered, occurs as suggestions for adjustments based on time, alternative projects, and strategies to address common difficulties students face.	*Students often find it challenging and complicated to create drawings. If they are given sufficient time, they usually manage to produce drawings that show simple objects with two views and measurements after some practice. Allow students extra time for this section.*
DP2 – the reasoning behind, and contextualised concrete examples of, the pedagogical ideas included in the teacher's guide.	Not very present overall. However, it is visible in the assessment section included in each chapter. It is also found in some introductory sections.	*Many students prefer to make drawings on graph paper, which can be a good starting point. However, when adding measurements and drawing lines between the grids, a drawing on graph paper can become unclear. […] Make students aware of this and let them try drawing their sketches and drawings on white paper.*
DP3 – supporting teachers' subject knowledge, making important content visible, and explaining it.	Appears to varying degrees. E.g. in the chapter about technological development work, there is a strong focus on essential subject content. Also found in some introduction sections.	*The circular motion refers to the frequent need to go back and improve technical solutions during development*
DP4 – support teachers' different needs for themselves and their students.	Examples are found when the guide points out content that may be difficult for students.	*Understanding the system boundary can be difficult.* (No support to the teachers on how to teach about this or explain boundaries in different situations.)
DP5 – provide teachers with examples of how work within technical disciplines is carried out in practice and can be part of the teaching.	Links to professions as a way of making lessons meaningful and relevant to the world outside school.	*Students may think that block programming is something you do in school, but block programming is also common in industry, for example, to control industrial robots or manufacturing machines.*
DP6 – support teachers to make the importance of technology for societal and everyday life visible.	Found in the chapter addressing the consequences of technology, also examples of historical perspectives and technological systems.	*Emphasise to students that the best approach is to minimise waste, meaning we should only buy products we truly need.*

Discussion

The analysed guide predominantly speaks *through* the teacher, as teacher guides often do (Remillard, 2000). The structure and content in this guide provide direct instructions that leave little room for adaptation, e.g. for diverse student groups. Fixed structures and specific instructions in guides can limit students' exposure to diverse perspectives and the broadness of the subject, as a previous study found that a textbook does not sufficiently cover a subject and that supplementary materials are needed (Engström et al., 2023). Lack of explicit explanations for methods can hinder teachers' understanding and ability to make informed decisions. Teacher guides can be a support for insecure teachers (van Steenbrugge & Ryve, 2018), but over-reliance on guides can lead to inadequate explanations and support for students. Even though guides should not replace teacher education or professional development, they can be useful for substitutes and as part of professional development if designed educatively.

The teacher's guide in this study is digital, which is a common format of teacher guides within this field. The digital format offers great opportunities and possibilities for redefining the materials (Puentedura, 2020), such as visualisations in the form of images, simulations, and video clips, both when talking *to* and *through* the teacher. However, the current guide does not take advantage of the benefits of digitalisation. Rather, it acts like a substitute for the analogue format (c.f. Puentedura, 2020). It mainly consists of text and images that are copies from the textbook. This is because the structure of the guide is designed to support the teacher by speaking through the teacher and linking directly to the book's pages, tasks, and so on.

Teacher guides should empower teachers to adapt and expand upon the material by speaking *to* teachers, not just *through* them. Teacher education programs should provide opportunities to explore different types of guides, encouraging reflection on their approaches and implications for teaching practice. This fosters flexible and reflective teaching practices.

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The Relationship Between Critical Thinking And Generative Artificial Intelligence: A Two-Way Street For Science Education

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The emergence of Generative Artificial Intelligence (GenAI) has presented new opportunities and challenges for developing critical thinking skills in science education. From the learning perspective, students' critical thinking skills are challenged during content creation (input) and evaluation (output) when interacting with GenAI. This process establishes a continuous loop that implicitly requires critical thinking to achieve desirable outcomes. From a teaching perspective, GenAI can be used as a tool to explicitly develop and assess critical thinking skills. During an exploratory seminar, we invited participants (N=26, working in pairs) to (a) rank science-related questions by the degree of critical thinking they are likely to provoke, (b) evaluate alternative GenAI-generated rankings as 'good', 'weak', or 'random' critical thinking, and (c) reconsider their own rankings after exposure to GenAI outputs and group reflection. We examined how difficult it is to judge critical thinking demands even without GenAI support, and how GenAI suggestions can shift participants' decisions. Descriptively, most participants revised at least one ranking, and a slight majority reported that GenAI influenced their final choices. We discuss these findings, arguing that GenAI can support critical thinking when positioned as an object of critique and a partner for structured reasoning rather than an answer engine.

Keywords: Critical Thinking; Generative Artificial Intelligence; Science Education

Introduction

The importance of critical thinking (CT) in science education is reflected in curriculum standards and educational goals across many countries and jurisdictions, highlighting its perceived value in developing scientifically literate individuals capable of reasoned analysis and decision-making in scientific contexts (Bailin, 2002). While CT is often cited as a key competency, its definition has become too broad to be helpful in science education, which stresses what scientists do: generate, test, and evaluate claims, data, and theories. This can be suggested as a definition of CT in the context of science education (Schmaltz et al. 2017). Such CT skills involve awareness of cognitive biases to avoid them, conducting impartial analyses, and using logical reasoning and evidence to support claims. These skills may enable students to question established social norms, challenge conventional wisdom, and expose societal inequities (O'Reilly et al., 2022; Larson et al., 2024).

Technology provides innovative tools and platforms for developing such CT skills, necessitating new teaching and assessment approaches in digital environments (Saadé et al., 2012). This necessity has become increasingly evident with the emergence of Generative Artificial Intelligence (GenAI) (Verma et al., 2023). CT and GenAI interaction encompasses both the learning and teaching perspectives. During learning, GenAI can challenge students' CT skills in (a) content creation (student input) and (b) content evaluation (GenAI output) (Larson et al., 2024). This continuous loop can extend as far as the student permits. While this interactive process between students and GenAI necessitates engaging students' CT to achieve desirable outcomes, the teaching perspective is also viable in utilizing GenAI specifically and explicitly

for CT skills development and assessment (Noroozi et al., 2024).

Given the relative novelty of this technology, only a limited number of research studies have investigated the impact of GenAI on students' critical thinking abilities (Bahroun et al., 2023), predominantly through indirect means, and even fewer have exploited GenAI as a tool for teaching and evaluating critical thinking. In the pertinent literature, scholars need to extend this research to address these questions and elucidate the potential outcomes that may be derived from the relationship between critical thinking and GenAI (Larson et al., 2024). In the context of science education, such research may yield a profound perspective for the development of future scientists and the advancement of broad scientific literacy.

This paper reports on an ESERA 2025 exploratory seminar that treated GenAI not primarily as a tutor but as a stimulus for reflection on what counts as ‘critical thinking’ in science-related questioning. Participants completed a brief activity sequence: initial ranking of four climate–agriculture related questions by how much critical thinking they provoke, classification of three GenAI-generated rankings as good/weak/random, followed by post-reflection re-ranking and a short survey on whether GenAI influenced their final decisions. We use the seminar outputs to illustrate (a) the intrinsic difficulty of evaluating critical thinking demands and (b) the ways GenAI can reshape judgments even in a meta-level task about critical thinking itself.

Theoretical framework

Critical thinking is a crucial 21st-century skill that enhances scientific understanding, promotes democratic citizenship, and develops higher-order cognitive abilities (Santos, 2017). Together with the above definition of CT skills in science education, it has the potential to humanize sciences and situate them in broader contexts, fostering inquiry and creativity through questioning, critique, and argumentation. It prepares individuals to tackle complex future challenges, supports informed decision-making on socio-scientific issues, and involves complex reasoning and evidence-based argument construction. CT skills are increasingly needed and challenged in an environment progressively influenced by advancing GenAI technologies (Zhai et al., 2024).

Prompting, or prompt engineering, provides a natural-language-based interface for GenAI, facilitating iterative and interactive exchanges between humans and GenAI systems in a collaborative creative process (Oppenlaender et al., 2024). Initial prompts are evaluated, and GenAI responses are assessed against students' intended outcomes. If GenAI's output is inadequate, the prompt is modified and re-evaluated until the desired result is achieved (Cain, 2023). This process implicitly promotes learning by reflecting on students' objectives, GenAI's capabilities and limitations, and language nuances.

While GenAI offers numerous opportunities to enhance education, critical thinking remains crucial to ensuring its effective, ethical, and pedagogically sound implementation in learning environments (Giannakos et al., 2024). The potential for biased or misleading information in GenAI outputs underscores the importance of critical thinking skills in recognizing and addressing these issues. The limitations of GenAI in nuance, context, and common sense necessitate human interpretation and evaluation to ensure meaningful learning experiences. Additionally, there are potential ethical concerns regarding data privacy, security, and intellectual property rights when using GenAI in educational settings that students should learn to address critically.

The overreliance on solutions generated by GenAI, without applying critical thinking skills in input development and output evaluation, may compromise students' capacity for independent

learning and conceptual understanding (Thiga, 2024). Therefore, there is a growing focus on developing effective teaching strategies and assessment methods to foster skills, including critical thinking, across all educational levels, from early childhood to higher education (O'Reilly et al., 2022) and teacher education (Verma et al., 2023). Recent research in the STEM education context demonstrates some attempts to develop frameworks for explicitly cultivating critical thinking utilizing GenAI tools as skill-teaching or assessment assistants (Lee & Low, 2024; Pantazatos et al., 2024; Shanto & Ahmed, 2024; Thiga, 2024).

Shanto & Ahmed (2024) proposed a framework that offers structured guidance for focused inquiry, gathering diverse perspectives, evaluating responses, synthesizing insights, and reflective learning to analyse and build upon GenAI-generated output critically. Lee and Low (2024) demonstrated the application of GenAI tools in parallel workshop activities, utilizing the Paul-Elder framework to foster critical thinking development among students. In concurrence, Thiga (2024) posited that critical thinking skills can be cultivated through GenAI by employing systematic and in-depth interrogation of tools' outputs. Similarly, Pantazatos et al. (2024) investigated the integration of a GenAI-based virtual assistant, with particular emphasis on its influence on students' critical thinking abilities.

Research consistently shows that GenAI can both enhance and inhibit students' critical thinking. Applied within structured educational frameworks, GenAI tools notably improve critical thinking (Lee & Law, 2024; Pantazatos et al., 2024). However, misuse can reduce motivation for independent inquiry and reflection, indicating a need for careful integration into curricula (Thiga, 2024). Research suggests that a deliberate, well-designed framework can significantly elevate critical thinking (Shanto & Ahmed, 2024). These findings highlight the importance of strategically guiding GenAI use to foster critical thinking skills in education.

Research studies on the impact of critical thinking on students' interaction with GenAI (learning perspective) and the utilization of GenAI to develop critical thinking skills (teaching perspective), explicitly call for further investigations to explore this intersection (e.g., Bahroun et al., 2023; Larson et al., 2024). While there have been attempts to identify the role of critical thinking in several STEM education domains, there is a deficiency in addressing the potential and challenges specifically in science education fields, where critical thinking is important (Bailin, 2002; Santos, 2017).

To begin addressing this gap, we designed an exploratory seminar that examines the two-way relationship between critical thinking (CT) and GenAI in science education: first, how participants' CT is mobilised when they evaluate and justify the quality of GenAI-generated reasoning (learning perspective), and second, how GenAI's outputs can shape or steer participants' subsequent judgements about what counts as "critical-thinking demanding" work (teaching perspective). In the context of this exploratory seminar study, we developed two research questions to be used as a principled starting point for future, more tightly operationalised research questions considering the participants' responses, feedback, and concerns.

RQ1 (CT → GenAI evaluation): To what extent can participants discriminate between GenAI-generated rankings that are presented as reflecting different levels of critical thinking, and how consistently do they make these classifications?

RQ2 (GenAI → CT evaluation): How does exposure to GenAI-generated rankings influence participants' subsequent judgements of critical-thinking demand?

Method

Seminar Participants

Participants (*N*=26) were attendees of the ESERA 2025 conference who voluntarily selected this exploratory seminar session. They comprised science education researchers and practitioners of diverse ages and national backgrounds, bringing a range of perspectives to the activity. All participants worked in self-selected pairs to facilitate collaborative discussion and decision-making during the activities.

Description Of The Seminar Activity

The activity was delivered through a structured online form (developed in Typeform) and consisted of five sequential phases. The scenario and the related questions were generated by GenAI to situate the task in a science-education context. An expert-derived rubric, based on the Holistic Critical Thinking Scoring Rubric ((Facione & Facione, 1994; Ramlo, 2019), was used to judge the CT demand of each question on a 1–4 scale (1 = least CT required, 4 = most CT). ChatGPT 5.0 was instructed to assess the CT provoked by these questions using the rubric and the result was calibrated by the researchers. Ultimately, the four questions had increasing CT complexity in the order: Q1 (score 1) < Q3 (2) < Q2 (3) < Q4 (4). This "ground truth" ranking (Q1 → Q3 → Q2 → Q4, from less to more provoking) was later used to generate example AI rankings and to evaluate participant responses.

Phase 1: Scenario and Initial Ranking
Participants first read a brief GenAI-generated scenario on climate change and agriculture, then individually ranked four GenAI-generated questions (Q1–Q4) from 1 (provokes the least critical thinking) to 4 (provokes the most critical thinking). This captured each pair's baseline judgment of which questions demanded more critical thinking.

The scenario text read:

> Uneven shifts in climate and atmospheric CO_2 are altering agricultural conditions. Evidence indicates both potential gains and losses that vary by method, timescale, and context, with cascading effects across production, trade, and food access amid uncertainty. Regional responses differ as growing seasons and crop suitability shift. Inferences about magnitude and direction often depend on data sources (observations versus model projections) and underlying methodological choices.

The four questions were:

> 1. What potential agronomic benefits associated with climate change have been observed or projected, and how can these be empirically evaluated across regions?
>
> 2. What lines of evidence both support and challenge the hypothesis that climate change may improve agricultural conditions in some locales, and how might methodological choices influence these findings?
>
> 3. How might shifts in climatic suitability and growing seasons affect crop selection, global trade flows, and food distribution, and what key uncertainties should be considered?
>
> 4. Which evidence-based decision-making framework could guide policies that both leverage potential local benefits and mitigate risks to food security, and how would trade-offs be justified?

Phase 2: Evaluation of GenAI Rankings

Next, participants reviewed three anonymized GenAI-generated rankings of the same questions, labeled "Ranking A," "Ranking B," and "Ranking C." They were told that one ranking was generated by a "Good Critical Thinker," one by a "Weak Critical Thinker," and one randomly, though the identities were not disclosed. Participants were asked to classify each ranking as *Good*, *Weak*, or *Random*, and identify which one they believed represented the best critical thinking ordering.

Phase 3: Justification

Participants were prompted to justify their choice of the "Good CT" ranking by writing a brief explanation of the criteria they used. This open-ended response captured their reasoning process and CT criteria (e.g., evidence use, synthesis, complexity) in their own words.

Phase 4: Re-Ranking

After completing the evaluation and justification phases, participants returned to their original question ranking and were invited to revise it based on the GenAI examples and their reflections. This phase allowed researchers to observe any shifts in judgement influenced by GenAI exposure.

Phase 5: Reflection On GenAI Influence

Finally, participants answered a Yes/No question on whether the GenAI-generated rankings influenced their revised decisions. If they answered "Yes," they were prompted to elaborate on what factors caused their change in ranking. This phase captured participants' perceived influence of GenAI on their thinking and decisions.

Data Collection and Analysis

The online form recorded all responses, yielding both quantitative and qualitative data. Quantitative measures included each pair's initial and final question rankings (for comparing changes), and their classification of the GenAI rankings (to assess identification accuracy of "Good/Weak/Random" rankings). Qualitative data included the textual justifications for selecting a particular ranking as "Good CT" and the open-ended reflections on GenAI's influence.

For analysis, we calculated simple descriptive statistics: the number of participants who correctly identified the AI's good-vs-poor CT rankings, the proportion who revised their question ordering, and the degree of alignment between participant rankings and the expert rubric before vs. after the GenAI intervention. The open-ended responses were reviewed to extract common themes regarding how participants judged critical thinking and why they did or did not alter their rankings.

Results

Discrimination Of GenAI-Generated Rankings (RQ1)

Overall, participants showed moderate success in distinguishing the quality of the AI-proposed question rankings. As summarized in Table 1, 9 out of 13 pairs (69%) correctly identified the "Good Critical Thinker" ranking generated by GenAI (the sequence aligning with the expert rubric). The remaining 4 pairs misidentified a suboptimal ranking as the "good" one – notably, 3 pairs were confused by the reversed (weak) ranking, labelling it as the best. Participants were most adept at spotting the nonsensical ordering: 11 pairs (85%) recognized the random ranking for what it was. Identification of the weak ranking was more challenging (only 8 pairs, 62%, labeled it correctly), with some of its misinterpretation being mistaken for either a good or random order. In fact, just over half of the groups (54%) managed to classify all three AI-generated rankings correctly. These results indicate that while many participants could discern obviously

poor vs. strong question orderings, a substantial minority struggled, particularly confusing the weakest ranking with the optimal one.

Table 1. Participant accuracy in classifying GenAI-generated rankings (*N*=13 pairs).

GenAI Ranking Type	Correct Identifications (n)	Accuracy (%)
"Good" ranking	9	69%
"Random" ranking	11	85%
"Weak" ranking	8	62%
All three classified correctly	7	54%

Participants' open-ended justifications shed light on the criteria they used to evaluate these rankings. Many participants based their judgments on the depth and complexity of thinking that questions in each ranking would demand. For example, responses frequently mentioned the inclusion of multiple perspectives, evaluation of evidence, and higher-order reasoning as signs of a "good" critical thinking question order. One pair explicitly referenced Bloom's taxonomy levels, noting that questions asking "how" and requiring synthesis or solution planning signaled higher cognition, whereas questions focusing on recall of details indicated lower critical thinking. Others emphasized the importance of evidence-based reasoning: e.g. "Being able to collate data, interpret data, and apply knowledge" was cited as a hallmark of the stronger ranking. In contrast, rankings where questions were simply factual or one-dimensional were seen as reflecting weaker critical thinking. These qualitative insights confirm that participants were attending to meaningful aspects of the questions (such as breadth of analysis, need for justification, and consideration of uncertainties) when judging the AI-generated rankings as strong or weak in CT terms.

Influence Of GenAI On Final Rankings (RQ2)

Exposure to the GenAI-generated examples had a notable impact on many participants' own question rankings. After evaluating the GenAI's rankings and reflecting, a majority of the pairs (8 of 13, ~62%) revised their original ranking of the four questions before final submission. In other words, only five pairs chose to keep their initial ordering unchanged through the activity. To gauge whether these revisions moved participants closer to the expert-defined ranking, we compared the alignment of each pair's ordering with the rubric-based "correct" order pre- and post-activity. Table 2 shows that alignment improved overall. Initially, only 1 out of 13 pairs (8%) had an exact match to the rubric's ideal order (Q1 < Q3 < Q2 < Q4). After the GenAI intervention and re-ranking, this number rose to 5 pairs (38%). Similarly, a simple alignment metric (total rank difference from the rubric, on a 0–8 scale) showed a substantial reduction: before the activity, participants' rankings deviated from the expert order by an average of 3.1 points; after revision, the average deviation dropped to 1.4. This indicates that many participants' final rankings were more in line with the expected difficulty order of the questions, suggesting a positive influence of the GenAI examples on their critical evaluation of the questions' demands.

Table 2. Alignment of participants' rankings with expert rubric (initial vs. final).

Alignment Metric	Initial Ranking	Final Ranking
Mean total difference (0–8)	3.1 ± 1.8	1.4 ± 1.1
Pairs with exact rubric order (n)	1 (8%)	5 (38%)

Qualitative self-reports from the reflection stage help explain how and why GenAI influenced (or did not influence) participants' thinking. Among the 13 pairs, 7 explicitly answered "Yes" – the GenAI rankings influenced their final decisions – while 6 reported no influence. Those who acknowledged influence often said that reviewing the GenAI-generated orderings prompted them to re-evaluate the criteria for critical thinking. For instance, one pair described how the AI

examples made them "think about the characteristics of critical thinking" and led them to consider "the depth of thinking and the amount of analysis" required by each question, even attempting to tie their reasoning to Bloom's taxonomy. Others noted that the contrast between their initial ranking and the GenAI "good" ranking revealed gaps or mistaken assumptions in their original thinking, prompting adjustments for a more evidence-based or multi-faceted approach. In a few cases, participants admitted the GenAI rankings caused confusion or doubt: "The results led me to get confused," one pair wrote, while another even joked that seeing an unexpected ordering made them "panic and question everything [we] knew about critical thinking." Nevertheless, even these instances of surprise or uncertainty often triggered deeper reflection on why a given question might be harder or easier than initially thought.

Conversely, the 6 pairs who reported no influence tended to stick with their initial reasoning despite the GenAI input. Some of them had already ranked the questions in an order close to the rubric's, so the GenAI examples may have simply affirmed their choices. Others indicated scepticism about the GenAI outputs, noting (for example) that the GenAI did not provide a rationale for its rankings, which limited its persuasive power. One pair commented that none of the AI-proposed orders matched exactly what they initially thought, but they did not fully trust those examples enough to overhaul their original ranking. This highlights that while GenAI can introduce new perspectives, participants with strong prior convictions or justified reasoning might resist changing their answers without a clear justification.

In the seminar activity, participants engaged with critical thinking in two distinct but complementary ways. First, they deployed critical thinking when analysing the cognitive demands of the four questions—drawing on reasoning, comparison, and synthesis to judge which required deeper thought. Second, they evaluated critical thinking when interpreting the logic and quality behind GenAI-generated rankings, reflecting on the reasoning implicit in each proposed sequence. This dual engagement allowed participants to not only practice critical thinking skills but also refine their understanding of what constitutes critical thinking in a science education context.

Discussion

This study contributes to a growing body of work examining how GenAI can be harnessed to support the development of critical thinking in science education. As previous research has noted, while CT is a central aim of science learning, its definition and operationalization often remain ambiguous (Bailin, 2002; Schmaltz et al., 2017). The seminar activity addressed this challenge by creating a concrete task in which participants had to weigh the cognitive demand of different questions and assess GenAI's ability to do the same. The difficulty many experienced in making these judgments reinforces the complexity of critical thinking as a construct, aligning with concerns raised by O'Reilly et al. (2022) and Larson et al. (2024) about the need for more precise and context-sensitive tools.

The outcomes also resonate with literature that has framed GenAI as a partner in learning rather than a passive tool (Lee & Low, 2024; Shanto & Ahmed, 2024). Participants who altered their rankings described how the AI examples prompted deeper reflection on what constitutes a high-quality, thinking-oriented question. Rather than adopting AI outputs uncritically, they weighed the underlying reasoning, compared it to their own, and sometimes changed course. This kind of iterative, evaluative engagement reflects the kind of interaction that Oppenlaender et al. (2024) and Giannakos et al. (2024) have highlighted as central to using GenAI to enhance learning.

Still, the variation in responses underscores the need for robust scaffolding and transparency

when incorporating GenAI in critical-thinking tasks. Some participants reported confusion or distrust toward the AI's rankings, particularly in the absence of explanations. This confirms the concerns raised by Thiga (2024) regarding potential misuse or misinterpretation of GenAI outputs and points to the importance of embedding such tools within pedagogically grounded frameworks. Educators must help learners develop both the cognitive and digital literacies required to critically assess GenAI-generated content.

Looking ahead, future studies should explore how this kind of seminar-based approach could be scaled, adapted for student populations, or integrated into pre-service teacher training. Further research might incorporate control conditions, longitudinal designs, or direct assessments of critical thinking before and after engagement with GenAI. In practical terms, educators might adopt similar ranking and justification tasks in classrooms to promote deeper reasoning about what makes a question cognitively demanding and how AI-generated reasoning can be critically assessed.

Ultimately, this work highlights a promising path forward: rather than viewing GenAI as a challenge to critical thinking, we can frame it as a site where critical thinking is activated, tested, and refined. By making GenAI both a partner in reasoning and an object of analysis, science educators can better prepare students (and themselves) for navigating the increasingly complex interplay of knowledge, technology, and judgment in a digital age.

Conclusions

The exploratory seminar provided valuable insights into how science education professionals engage with GenAI-generated content when evaluating and re-evaluating the critical-thinking demand of science-related questions. Participants were moderately accurate in distinguishing between question rankings of varying quality, and their reasoning often drew on meaningful indicators such as depth of analysis, evidence use, and synthesis. Moreover, many participants revised their original rankings after reflecting on the GenAI-generated examples, resulting in greater alignment with expert expectations. These findings suggest that while distinguishing levels of critical thinking remains a nuanced and challenging task, especially when mediated by GenAI, structured activities such as this can foster improved judgment and metacognitive awareness.

Crucially, the results point to the value of positioning GenAI not as an authoritative answer engine but as a prompt for reflection and critique. Participants' engagement with the AI rankings influenced their decisions in ways that highlighted both the potential and the limitations of GenAI in supporting critical thinking. This two-way interaction, where GenAI both elicits and is subject to critical evaluation, offers a promising direction for future teaching and research practices in science education.

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Exploring The Use Of ChatGPT In Science Lesson Planning

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Generative AI (GenAI) is increasingly recognized for its potential to support teachers in tasks such as lesson planning. However, its limitations, including inaccuracies in generated responses, make it essential for teachers to critically evaluate its outputs. This study explores the use of GenAI in science lesson planning through the lens of Pedagogical Content Knowledge (PCK). The research is structured in two phases. In the first phase, we examined the use of ChatGPT in science lesson planning by engaging with the tool as researchers, focusing on how lesson plan suggestions generated reflect components of PCK. Building on the findings from this phase and insights from related literature, the second phase investigates how primary school teacher students utilize ChatGPT for lesson planning informed by PCK within the context of a university seminar. Findings from the first phase, based on qualitative content analysis, indicate that when ChatGPT is guided by PCK-informed layer prompts and supported by relevant reference texts, it generates more pedagogically appropriate lesson plan suggestions. Results from the second phase show that, after being introduced to PCK and prompt engineering strategies, primary school teacher students increasingly employed layer prompts, particularly Natural Language Instruction and Follow-up prompt types, and incorporated PCK components in more meaningful ways. Overall, the findings support the conceptualization of ChatGPT as a co-designer in science lesson planning, rather than as a substitute for teachers' pedagogical judgement.

Keywords: artificial intelligence, pre-service teacher education, instructional design

Introduction

Generative AI (GenAI) is widely recognized for its generative capabilities in producing human-like text (Chan & Colloton, 2024). In the field of education, GenAI tools such as ChatGPT show potential to support teachers in lesson planning and creating teaching materials (Calvo-Utrilla et al., 2025; Choi, 2025; Cooper, 2023; ElSayary, 2023; ElSayary et al., 2025). However, concerns about inaccuracies, biases, and ethical issues in its outputs (Avraamidou, 2024; Calvo-Utrilla et al., 2025) highlight the importance of critical evaluation and responsible use by educators (Blonder & Feldman-Maggor, 2024; UNESCO, 2023). Prompt engineering has emerged as an essential skill for educators to optimize GenAI outputs, forming a critical part of their Technological Pedagogical Content Knowledge (TPACK) in the age of AI (Blonder & Feldman-Maggor, 2024; UNESCO, 2023). For instance, effective strategies may include instructing GenAI to adopt a specific persona, using step-by-step layer prompts also referred to as chain of thought prompting, and supplying reference texts such as scientific papers to reduce inaccuracies and minimize fabricated responses (Atlas, 2023; Blonder & Feldman-Maggor, 2024; Knoth et al., 2024; Wei et al., 2023). Nevertheless, human oversight remains imperative to address these limitations (UNESCO, 2023).

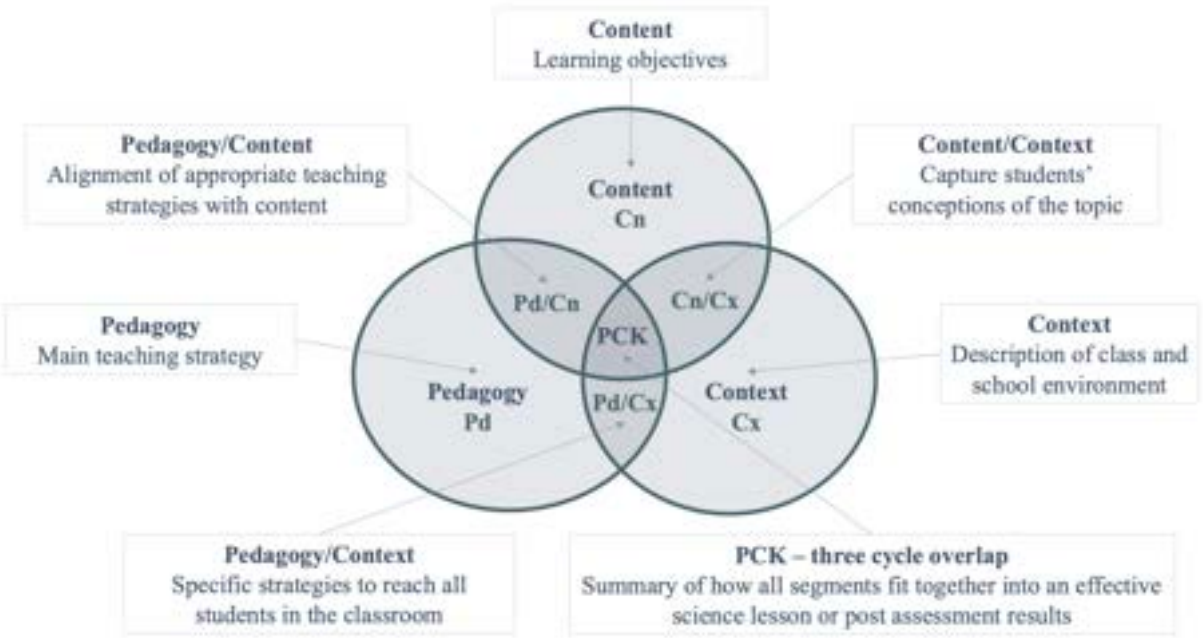
Research on the use of GenAI in lesson planning demonstrates its ability to create lesson plans for specific science topics based on inquiry-based teaching approaches (Cooper, 2023; Großmann et al., 2025), with evidence showing that its output improves when guided by iterative prompts (Hashem et al., 2024; Peikos & Stavrou, 2025). From the teachers' perspective, GenAI tools such as ChatGPT are valuable for generating innovative ideas, enhancing lesson quality through engaging activities, supporting personalized learning, aligning lessons with real-life scenarios to boost student motivation and saving time. Nevertheless, both researchers and teachers emphasize that GenAI should serve as an assistant rather than a substitute for teachers. They also raise

concerns about the reliability of its outputs, such as potential weaknesses in content accuracy and in the provision of meaningful pedagogical suggestions (Cooper, 2023; ElSayary, 2023; ElSayary et al., 2025; Großmann et al., 2025; Uğraş et al., 2025).

Building on the above literature findings, it is evident that GenAI holds significant potential for assisting with lesson planning, although this potential is interwoven with limitations regarding the accuracy of information. Therefore, it is essential for teachers to critically evaluate GenAI outputs when using it to support lesson planning (UNESCO, 2023), drawing on PCK (Blonder et al., 2025; Feldman-Maggor et al., 2024; Großmann et al., 2025; Peikos & Stavrou, 2025) as a foundational knowledge base to enhance its responsible use.

PCK has been established as a core construct for understanding teaching effectiveness and informing teacher professional development. PCK is "the knowledge of, reasoning behind, and planning for teaching a particular topic in a particular way for a particular purpose to particular students for enhanced student outcomes" (Gess-Newsome, 2015, p. 36). Over more than four decades of PCK research following Shulman's seminal work (Shulman, 1986), several PCK models have been proposed, leading to the formulation of the Refined Consensus Model of PCK (Carlson et al., 2019). Across these models, key PCK components have been consistently identified, including knowledge of students' understanding, instructional strategies, curriculum, assessment, context, content knowledge, pedagogical knowledge, and orientations toward teaching science. These components are intrinsically interconnected in practice, and their integrated enactment constitutes the core of effective science teaching (Carlson et al., 2019; Chan & Hume, 2019; Gess-Newsome, 2015; Magnusson et al., 1999; Park & Oliver, 2008). The Refined Consensus Model (Carlson et al., 2019) conceptualizes PCK across three interrelated realms: collective PCK, referring to shared professional knowledge; personal PCK, representing the knowledge and skills teachers develop through experience; and enacted PCK, referring to the knowledge and skills drawn on when planning, teaching, and reflecting on instruction and student outcomes.

Figure 1. Venn diagram of PCK for science lesson planning, adapted from Otto and Everett (2013).



Focusing more closely on enacted PCK, particularly when teachers plan instruction (Carlson et al., 2019), Otto and Everett (2013) have developed an innovative teaching strategy for introducing PCK concepts to pre-service elementary teachers by utilizing a three-circle Venn diagram for

science lesson planning (Figure 1). The diagram featured overlapping circles representing Pedagogy (e.g., teaching strategies), Content (e.g., learning objectives), and Context (e.g., classroom environment), Pedagogy/Context (e.g., specific strategies to reach all students in the classroom), Pedagogy/Content (e.g., aligning appropriate teaching strategies with content), Content/Context (e.g., capturing students' conceptions of the topic) as well as the PCK overlap summarizing how these components fits together into an effective science lesson (Otto & Everett, 2013).

Lesson planning is a key component of teachers' professional competence, requiring the application of PCK to design and justify pedagogical decisions (Großmann & Krüger, 2024). In the era of GenAI, within the context of a teacher-AI co-design process for lesson planning (UNESCO, 2023), PCK is proposed as a valuable framework for crafting effective prompts and critically evaluating the pedagogical quality of GenAI outputs (Blonder & Feldman-Maggor, 2024; Peikos & Stavrou, 2025). To explore these opportunities and challenges, this research is structured in two phases. In the first phase, we investigate the use of ChatGPT in science lesson planning, with the goal of identifying the characteristics of ChatGPT-generated lesson plan suggestions through the lens of PCK. Building on the findings from the first phase and insights from related literature, in the second phase, we explore how primary school teacher students integrate ChatGPT into their lesson planning process within the framework of PCK. The research is guided by the following research questions (RQs):

- RQ1: What are the characteristics of lesson plan suggestions produced in ChatGPT's outputs during collaboration between researchers and ChatGPT, in terms of PCK?
- RQ2: How do primary school teacher students utilize ChatGPT for lesson planning, focusing on (a) the types of prompts they used and (b) the PCK components incorporated into the prompts?

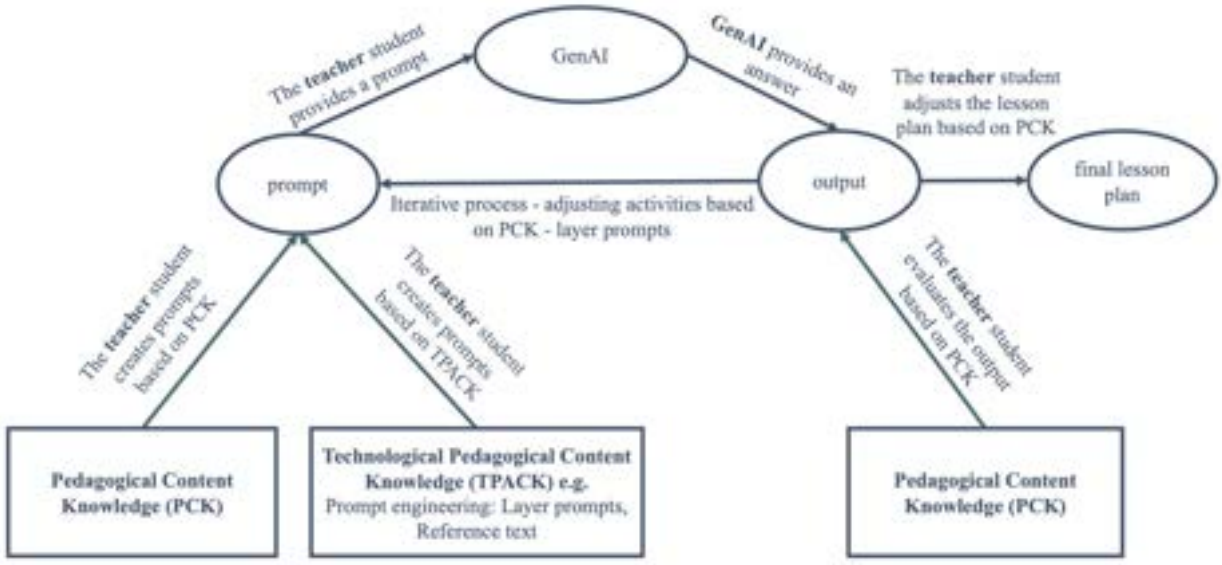
Methods

The Context

In the first phase, the researchers examined the use of ChatGPT for science lesson planning through the lens of PCK by using the tool themselves to design lesson plans. To this end, four interactions with ChatGPT were designed to generate lesson plans, each differing in prompt engineering strategies and PCK integration. ChatGPT was instructed to adopt the persona of an expert in science lesson planning for primary schools (Atlas, 2023; Chan & Colloton, 2024). The first interaction used a single prompt to create a lesson plan based on the 5Es instructional model for the topic of floating, sinking, and density, targeting 5th-grade primary school students. The second interaction introduced specific learning goals related to declarative and procedural knowledge. The third and fourth interactions employed layer prompts in a conversational manner to address several PCK aspects. For instance, ChatGPT was asked to describe activities to uncover students' misconceptions about floating and sinking (Content/Context overlap). The fourth interaction differed by providing a reference text i.e., an open-access scientific paper relevant to the topic. This phase resulted in the formulation of guidelines for the use of GenAI as a co-designer of lesson plans (Peikos & Stavrou, 2025) (Figure 2). Briefly, the guidelines indicate that teachers could initiate the process by formulating prompts that integrate components of PCK, including explicit learning goals, instructional strategies, and students' conceptions. Drawing on prompt engineering, a TPACK-related feature, they are encouraged to use layer prompts in a conversational manner, offering clear, step-by-step guidance that embeds PCK elements. In addition, ChatGPT is provided with relevant reference texts, such as scientific papers related to the instructional topic. The resulting output should be critically examined by the teacher through

the lens of their PCK and iteratively refined to address issues such as student misconceptions and grade-level appropriateness. Finally, teachers could select and adapt the proposed activities to their specific instructional context, leading to the development of the final lesson plan (Peikos & Stavrou, 2025).

Figure 2. Guidelines for student teacher–GenAI co-design of lesson plans based on PCK (adapted from Peikos & Stavrou 2025).



In the second phase, within the context of a semester-long university seminar, primary school teacher students were introduced to the use of GenAI for science lesson planning through the free web-based version of ChatGPT (GPT-4o). Based on the guidelines derived from the first phase, activities were designed to support the use of ChatGPT as a co-designer. The participants studied material related to the benefits and challenges of using ChatGPT, prompt engineering, and PCK. In addition, the researchers developed a pedagogical agent, Anna (Figure 3), within an augmented reality environment, which provided primary school teacher students with guidance during the development of lesson plans, particularly with respect to prompt engineering and the PCK diagram proposed by Otto and Everett (2013). For example, by selecting the Content/Context option (Figure 3), participants receive information, both in written and oral form, regarding the meaning of the Content/Context overlap, which focuses on the identification of students' ideas related to the Content, as well as on the elicitation of students' alternative ideas or prior knowledge. Moreover, they are provided with an example of a related prompt, such as: "Describe a structured activity aimed at eliciting students' alternative ideas about [insert the concept/phenomenon]".

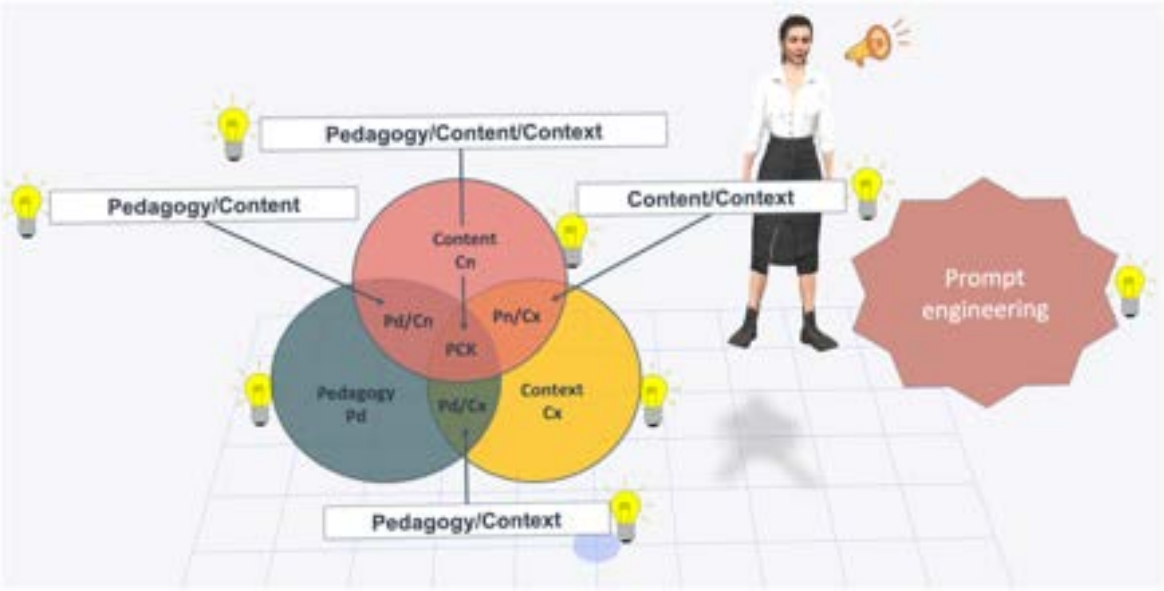
Participants

The participants were 18 primary school teacher students in their third and fourth year of study, who attended most of the seminar sessions.

Data Collection And Analysis

For RQ1 (first phase), the data sources comprised texts produced through four interactions between the researchers and ChatGPT during the lesson planning process, with a focus on ChatGPT's outputs.

Figure 3. Augmented reality pedagogical agent Anna.



For RQ2 (second phase) qualitative data were collected through the discussions between primary school teacher students (working in teams of two) and ChatGPT during the lesson planning process. The focus was on the prompts formulated by the teacher students. Data were collected at three time points, as participants were engaged in the creation of three lesson plans: (a) before the introduction to GenAI and PCK, (b) after the introduction to GenAI and PCK, and (c) after the provision of feedback by the instructor on the primary school teacher students–AI co-design lesson planning process.

For RQ1 and RQ2b, the texts were analysed deductively in order to categorize coding units into predefined PCK components (Chaitidou et al., 2018; Otto & Everett, 2013; Peikos & Stavrou, 2025), namely Pedagogy, Content, Context, and their overlaps, with additional subcategories formed inductively from the data (Table 1).

Table 1. Data coding for RQ1 and RQ2b: PCK components, based on Chaitidou et al. (2018), Otto & Everett (2013) and Peikos & Stavrou (2025)

Category	Description	Examples of subcategories
Content	Learning objectives	Declarative knowledge, Procedural knowledge,
Context	Descriptions of class and school environment including resources and time constraints	Grade level, List of resources, Students' characteristics, Time constraints
Pedagogy	Main teaching strategy	5E format
Content/ Context	Capture students' conceptions of the topic	Activity to identify specific students' misconceptions, Activity to identify students' prior knowledge/ideas/common misconceptions
Pedagogy/ Context	Specific strategies to reach all students in the classroom	Activity to address common misconceptions, Activity to address a specific misconception
Pedagogy/	Alignment of appropriate	Activity aligned with specific learning objective,

Content	teaching strategy with content	Activity with specific teaching strategy for the content
PCK	Summary of how all segments fit together/proposed assessments	General assessment activity, Assessment activity based on specific characteristics

For RQ2a, concerning the types of prompts used by primary school teacher students, the texts were analysed deductively based on the prompt types proposed by Şimşek (2025), which distinguishes six types of prompts: (a) Natural Language Instruction (NLI), (b) Question (Q), (c) Follow-up (FU), (d) Extend (E), (e) Search Query (SQ), and (f) Emotive Feedback (EF), as well as combinations of these types such as Natural Language Instruction & Follow-up (Table 2).

Table 2. Data coding for RQ2a: Types of prompts (Şimşek, 2025, p. 11413).

Category	Definition
Natural Language Instruction (NLI)	A prompt formulated as an explicit instruction for a task in natural language.
Question (Q)	A prompt that begins with a question word and is formulated as a direct or indirect interrogative statement.
Follow-up (FU)	A prompt related to the response given by ChatGPT in the previous step.
Extend (E)	A prompt that encourages ChatGPT to extend or continue an input data example.
Search Query (SQ)	A prompt, such as a search query, typed into a search engine to access information.
Emotive Feedback (EF)	A prompt that provides no contribution to the task and offers positive or negative feedback to ChatGPT as if it were human.

Results

In the following paragraphs we present the preliminary findings of this study. Concerning RQ1 “How do lesson plans generated by ChatGPT reflect the components of PCK?” we found that, in relation to the overlap between Content/Context, ChatGPT demonstrated potential to create activities aimed at uncovering students’ prior knowledge and misconceptions. In the absence of detailed prompts, the model often provided generic activities. However, when guided by specific layer prompts, ChatGPT produced more structured and targeted strategies, such as concept mapping. Concerning Pedagogy/Context overlap layer prompts enhanced ChatGPT’s ability to propose strategies for addressing student misconceptions and accommodating learning diversity. In early interactions, the model’s outputs lacked targeted activities to address specific misconceptions. However, after providing related prompts, ChatGPT began generating inquiry-based tasks designed to challenge common misconceptions, such as the belief that “heavier objects always sink”. Furthermore, regarding the Pedagogy/Content overlap in its initial responses, ChatGPT frequently suggested both qualitative and quantitative approaches to

teaching the concepts of floating and sinking. However, when considering the Context, i.e., the grade level of primary school students, literature suggests that qualitative approaches, such as visual representations, are more appropriate than quantitative approaches, such as the formula d=m/v (Zoupidis et al., 2021). With the use of layer prompts and the provision of reference text, ChatGPT's outputs in the fourth interaction became more aligned with students' grade, emphasizing qualitative instructional approaches. A detailed presentation of the results related to RQ1 is provided in Peikos and Stavrou (2025).

Regarding RQ2a, which focuses on the types of prompts used by primary school teacher students, a noticeable shift was observed during the second and third lesson planning processes. In particular, prompts identified as Natural Language Instruction became more prevalent. This suggests that, once introduced to GenAI, primary school teacher students increasingly framed their interaction with ChatGPT through explicit task-oriented instructions expressed in natural language. For example, one team formulated the following prompt:

> Take the role of an expert in science education for the 5th grade science lesson. Help me create a one-hour lesson plan using simple everyday materials, to teach the phenomenon of floating and sinking by explaining it through density, according to the 5E instructional model…

Similarly, Natural Language Instruction combined with Follow-up was observed more frequently during the second and third lesson planning processes. This category refers to prompts formulated as explicit instructions in natural language that build directly on the response provided by ChatGPT in a previous step. For instance, a team of students wrote:

> For the activity in the engagement phase, according to what we said above, I would like it to be in the form of a short story that narrates a problem related to the phenomenon of sinking and floating, so that students' alternative ideas can become evident based on the solutions they will give. Make it in the form of a worksheet that will include an image showing the problem of the story.

Regarding RQ2b "How do primary school teacher students utilize ChatGPT for lesson planning, focusing on the PCK components incorporated into the prompts?" notable changes were observed in the Content category. In the first lesson planning process, teacher students' prompts that explicitly referred to specific learning objectives were limited. Most prompts either addressed the topic in general terms or asked ChatGPT to define the learning goals. For example, a team of students submitted the following prompt to ChatGPT:

> [Create a teaching scenario for the subject of Physics. It is intended for 5th grade primary school students. The topic is floating-sinking and density.] Write the objectives in detail.

In contrast, during the second and third lesson planning processes, teacher students clearly incorporated specific learning objectives into their prompts. These objectives were connected to both declarative and procedural knowledge, indicating a more explicit integration of Content. For instance, a team of students submitted the following prompt to ChatGPT:

> […Help me create a lesson plan on density and its relationship to floating and sinking for 5th-grade students, based on the 5E instructional model ...] The learning objectives are: (a) for students to understand the rule governing whether an object floats or sinks based on its density; (b) for students to state that density is a characteristic property of a material; and (c) for students to be able to apply strategies for controlling variables…

Examining more closely the overlaps among the PCK components, notable patterns were identified. With regard to the Pedagogy/Context overlap, most primary school teacher students'

prompts in the second and third lesson planning processes asked ChatGPT to propose resources to support the planned activities. These resources included, indicatively, videos, simulations, models, illustrations, storytelling, and worksheets. For example, one team of primary school teacher students wrote:

> Propose the use of supportive educational materials such as simulations and models that contribute to the understanding of the concept of heat transfer by conduction in metals.

In addition, during the second and third lesson planning processes, primary school teacher students more frequently asked, through their prompts, for activities that would connect to students' experiences, foster collaboration, and elicit students' interest. Regarding the Content/Context overlap, prompts explicitly related to students' prior knowledge and misconceptions were very limited in the first lesson planning process. In contrast, during the second and third lesson planning processes, primary school teacher students asked ChatGPT to develop activities explicitly aimed at identifying students' prior knowledge and misconceptions. For example, a team of students wrote:

> In the Exploration phase, propose one or more hands-on activities during which students will express their initial conceptions and reveal their misconceptions, focusing on the misconception that the temperature of water rises above 100 degrees Celsius while it is boiling.

Conclusion

In the first phase, the study examined the use of ChatGPT for science lesson planning through the lens of PCK by engaging the tool in a series of lesson planning interactions conducted by the researchers. These interactions varied in both prompt engineering strategies and levels of PCK integration. The findings demonstrate that incorporating PCK elements into prompts, using layer prompts, and providing ChatGPT with reference texts related to the instructional topic may enhance the integration of PCK components in GenAI-generated outputs related to the lesson plans. In this phase, the PCK framework appeared meaningful for supporting responsible interactions with ChatGPT in the context of teacher and GenAI lesson co-design. It provided a coherent knowledge base for both crafting pedagogically informed prompts and critically evaluating ChatGPT's responses in relation to science lesson planning (Peikos & Stavrou, 2025).

Building on these insights, the second phase examined how primary school teacher students utilized ChatGPT for science lesson planning within the context of a university seminar, following their introduction to prompt engineering strategies and the PCK framework. The findings indicate that the students were able to formulate prompts grounded in their PCK, with particular emphasis on overlaps such as Pedagogy/Context, as well as Content/Context. In parallel, they engaged with aspects of TPACK, particularly in relation to prompt engineering. Rather than limiting their interaction to ChatGPT's initial responses, the students engaged in an iterative prompting process guided by their PCK, progressively refining the generated outputs. Through the use of layer prompts, mainly in the form of Natural Language Instruction and Follow-up prompt types, they adapted the proposed activities to better align with pedagogical goals and classroom context.

Grounded in the Refined Consensus Model of PCK (Carlson et al., 2019), the findings indicate that teachers' engagement with GenAI tools for lesson planning, as an activity situated within enacted PCK realm, involves the design, reflection, and justification of lesson plans drawing primarily on their personal PCK, while also being shaped by collective PCK and the particularities of the learning context. Within this process, research-based literature on the

teaching and learning of specific science concepts, as an aspect of collective PCK, may be provided to GenAI tools as reference material, thereby informing lesson plan suggestions and potentially reducing inaccuracies. In parallel, responsibility for critically evaluating GenAI-generated outputs remains with the teacher. Drawing on their personal PCK, teachers are required to evaluate the pedagogical soundness of proposed activities, the accuracy of the scientific content, and their suitability for the specific classroom context. Taken together, these findings support the view that GenAI should be conceptualized as a co-designer in the lesson planning process, rather than as the primary designer of instructional plans.

The results underscore the importance of preparing teachers to engage with GenAI through a strong grounding in PCK, combined with prompt engineering skills. Teacher education and professional development programmes should therefore explicitly address this interplay, as it may support more responsible and pedagogically informed integration of GenAI into science lesson planning. Moreover, GenAI can be positioned not merely as a time-saving assistant, but as a tool for supporting teachers' reflection on their own PCK (Blonder et al., 2025). When used in a critical way and potentially supported by pedagogical agents that scaffold interaction between teachers and GenAI, such engagement may help raise teacher teachers' awareness of their pedagogical reasoning and instructional decision-making in science lesson planning.

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Artificial Intelligence In Teacher Education: Attitudes, Usage, And The Road To AI Literacy

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The rapid development of artificial intelligence is also having an impact on the education sector and placing new demands on the professionalisation of future teachers. This study examines the extent to which teacher trainees use generative AI in their studies and how they assess their attitudes and skills with regard to this technology. To this end, two cross-sectional surveys were conducted via online questionnaire in April 2024 (n = 221) and April 2025 (n = 204). The results show a significant increase in AI use between 2024 and 2025, especially in the study-related use outside of lectures, while its use in courses remains comparatively low despite the increase. It also shows that higher use is associated with an increase in positive and a decrease in negative attitudes. There is also a positive correlation between usage rates and subjectively perceived AI literacy, AI self-efficacy and AI self-competence. In 2025, positive attitudes and all recorded perceptions of competence increase significantly, while negative attitudes remain largely stable as compared to 2024.

Keywords: AI usage, AI attitudes, AI literacy

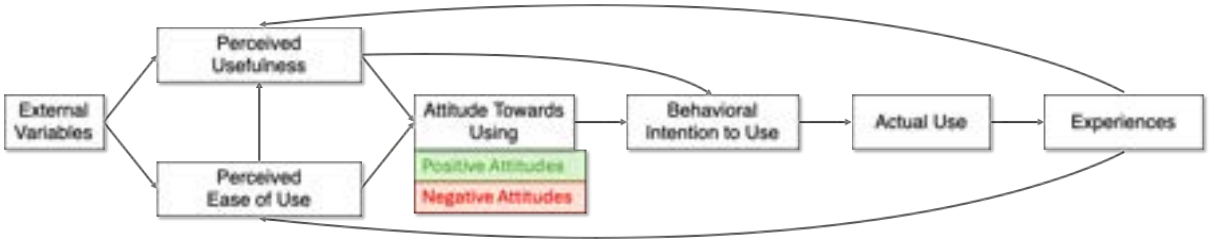
Introduction And Theoretical Background

The advancing digitalisation of schools is expanding the possibilities for the didactic and methodological design of lessons. To exploit this potential, it does not suffice to simply replace analogue media with digital media. Rather, teaching and learning processes must be transformed (Puentedura, 2006). These changes keep presenting teachers with new challenges (Eickelmann, 2018; Scheiter, 2017). It is thus not only important to master digital technologies but above all to use them in a didactically reflective manner. The introduction of ChatGPT at the end of 2022 marked the beginning of a rapid and ongoing development of artificial intelligence (AI), which has also triggered changes in the field of education. In this context, current and future teachers bear a great responsibility (Europäische Kommission, 2022) as they are expected to systematically integrate teaching and learning with and about AI into their subject teaching and prepare their students to use this technology competently (Huwer et al., 2024). In a rapidly evolving digital world, the continuous training and further education of teachers appears to keep gaining importance. Teacher trainees are the prospective teachers who must take on these tasks in future. Even though as digital natives they are considered to be tech-savvy, research paints a more differentiated picture: During their studies, teacher trainees often gain too little practical experience with digital technologies (Eickelmann et al., 2019), show competence deficits in the area of digitalisation compared to students of other disciplines (Senkbeil et al., 2020), and rate their digital competences as only mediocre (Drossel & Eickelmann, 2018). The discrepancy between digital requirements and insufficient experience in teacher training programmes highlights an urgent need for action.

Therefore, it seems important that teacher trainees are willing to engage with AI in order to develop AI competences (Huwer et al., 2024). In the Technology Acceptance Model (Figure 1), two factors influencing a person's attitudes and thus their acceptance of a technology can be identified: perceived usefulness and perceived ease of use. These two factors result in positive and negative attitudes which shape a person’s overall attitude. A positive attitude promotes the intention to use the technology, whereas a negative attitude reduces the intention to use. In

addition, the intention to use a technology can also be influenced independently of a person's individual attitudes. This is the case, for example, when the added value or efficiency gains offered by the technology are obvious. The intention to use ultimately determines the actual use of a technology. Through every use of a technology, a personal automatically gains experience which is why this component may be added to the Technology Acceptance Model. The successful application of a technology can also increase its perceived usefulness and have a positive effect on attitudes, as, for example, experienced users recognise more possible applications for a technology and find it more intuitive to use due to their familiarity with it.

Figure 1. Technology acceptance model enhanced by experiences (according to Davis, 1986).



Research Questions And Hypothesis

This article focuses on the use of generative AI in teacher training programmes and the attitudes and perceived competence of students. It also examines changes between 2024 and 2025. The following research questions and hypotheses specify this research interest.

Q1: To what extent do teacher trainees use AI?

New technologies, such as AI, can often only be used in university courses after a delay, especially when licences must first be purchased and data protection issues clarified. Furthermore, the use of AI in higher education has so far been described mainly through isolated best practice examples, while systematic evaluations of teaching concepts are still pending (Huwer et al., 2024). While universities must first clarify formal and legal criteria, students can immediately access free offers and use AI for interactive and adaptive learning, for example, or as a personal learning coach (Baidoo-Anu & Owusu Ansah, 2023; Baig & Yadegaridehkordi, 2024; von Garrel & Mayer, 2025). According to the TAM model (Davis, 1986), the perceived usefulness and low-threshold accessibility of AI tools increases the likelihood of use. This leads to the following hypothesis:

H1.1: Teacher trainees' out-of-courses use of AI tools is higher than their use in courses.

Q2: To what extent are teacher trainees' attitudes and perceived AI competence influenced by their AI use?

Surveys on the use of generative AI show that a large number of students already use this technology for their studies (Gottschling et al., 2024; Lutz et al., 2025; von Garrel & Mayer, 2025). Based on the extended TAM model (Figure 1), it can be assumed that positive attitudes promote the intention to use a technology and thus the actual use, while negative attitudes tend to inhibit both. At the same time, every experience with a technology contributes to a change in perceived usefulness and perceived ease of use, which in turn affects a person's attitudes. While successful applications have a positive effect, unsuccessful application can have a negative impact. In addition, little or no experience with a technology can be associated with increased uncertainty and fear, which inhibits technology acceptance (Dönmez-Turan & Kır, 2019). This leads to following hypothesis:

H2.1: Students with greater AI use rate the chances of AI more positive and the risks less negative.

Competences are not built by the acquisition of cognitive skills and abilities alone, but also by their successful and responsible application in various situations (Weinert, 2001). Competent AI use thus requires active use of the technology. Practical experience also helps to familiarise oneself with the possibilities and limitations of generative AI. This allows the technology to be used in a more targeted, effective, and reflective manner. As a result, the successful application of AI tools becomes more likely. In the study by Süße & Kobert (2023) high correlation effects between the use of generative AI and perceived learning success were found among some students. According to Bandura (1997), perceived successes strengthen one's self-efficacy and thus confidence in one's competence, even in challenging situations. This leads to following hypothesis:

H2.2: Students with a higher usage behaviour rate their AI competences, their AI self-efficacy, and their AI self-competency higher.

Q3: How did usage behaviour, attitudes, and perceived AI skills change between 2024 and 2025?

Generative AI is subject to particularly dynamic technological development, which is accompanied by continuous improvement and increased performance. The further development of new language models means that the up-to-then most recent versions are made available free of charge as previous versions. That way, increasingly better versions are made available free of charge. For students, this means that AI tools with a growing range of functions can be integrated into everyday student life without financial barriers. Better and more powerful systems increase the perceived usefulness, which, according to the TAM model (Davis, 1986), leads to a more positive attitude and more frequent use of the technology. Based on a total of 49 study results on the usage behaviour of generative AI among students, Von Garrel & Mayer (2025) performed a regression analysis that shows an increase in usage behaviour from 2023 to early 2025. Thus, the following hypotheses arise:

H3.1: In 2025, teacher trainees' study-related use of AI is higher than in 2024.

H3.2: In 2025, teacher trainees associate fewer risks and more chances with the study-related use of AI tools than in 2024.

H3.3: In 2025, teacher trainees rate their AI competence, AI self-efficacy, and AI self-competency higher than in 2024.

Study description

Study Design

This study aims to record the usage behaviour, attitudes, and subjectively perceived skills of teacher trainees with regard to generative AI. To this end, cross-sectional surveys were conducted in April 2024 and April 2025 using an online questionnaire. Participation in the surveys was voluntary, and data collection was pseudonymised by creating an acronym from personal queries. This code shows that the overlap between students who participated in both surveys is less than 1 percent. A longitudinal analysis of the data therefore does not appear to be meaningful, so the data collected in 2024 and 2025 are considered statistically independent in the analysis.

Sample

Table 1 provides an overview of the teacher trainees participating in the surveys in 2024 and 2025. The sample sizes of both studies are comparable with n = 221 (2024) and n = 204 (2025). The gender distribution is similar in both years, with a significantly higher proportion of female students There were only a few participants in both surveys who stated that they were non-binary. In Germany, teacher training is organised according to school type and comprises five types of

school, each of which has its own degree programme. The percentage distribution of students across the school types roughly corresponds to the number of students enrolled in each school type. The imbalance is therefore not due to the survey design. In both surveys, most students were in their third to sixth semester. Plausible explanations for this are that the standard time to degree vary between seven and nine semesters depending on the type of school and that the surveys were conducted by lecturers as part of didactic courses. These are typically attended by students in the middle of their studies.

Table 1. Sample composition.

	2024					2025				
Gender	f	m	d			f	m	d		
	161	59	1			144	57	3		
Type of school	GYM	GS	FS	RS	MS	GYM	GS	FS	RS	MS
	36.7%	34.8%	15.8%	7.7%	5.0%	40.2%	28.4%	14.7%	10.8%	5.9%
Semester	1 - 2	3 - 4	5-6	7-8	9-10	1 - 2	3 - 4	5-6	7-8	9-10
	10.4%	36.7%	22.2%	15.4%	10.4%	8.1%	25.3%	27.1%	14.5%	13.1%
	11-12	13-14	>14			11-12	13-14	>14		
	2.3%	1.4%	1.4%			3.2%	0.5%	0%		

Operationalisation And Test Instruments

The use of generative AI was assessed using two single-item measures, one relating to courses ("Was artificial intelligence used as a tool to support the learning process in courses you attended in previous semesters?") and the other relating to individual study-related out-of-course use ("Do you use AI tools in your studies?"). Both items were rated on a four-point frequency scale (never = 0, rarely = 1, occasionally = 2, regularly = 3).

To assess teacher trainees' attitudes towards generative AI, the General Attitudes towards Artificial Intelligence Scale (GAAIS, Schepman & Rodway, 2023) was adapted. The original scale comprises a total of twelve items on positive attitudes and eight items on negative attitudes, each rated on a five-point Likert scale (strongly disagree = 0, disagree = 1, neutral = 2, agree = 3, strongly agree = 4). For the present study, three positive items (e.g., "I am interested in using artificially intelligent systems in my daily life") and three negative items (e.g., "I think artificial intelligence is dangerous") were selected. The reliabilities are in an acceptable to good range, with $\alpha = 0.76$ (positive attitude) and $\alpha = 0.74$ (negative attitude).

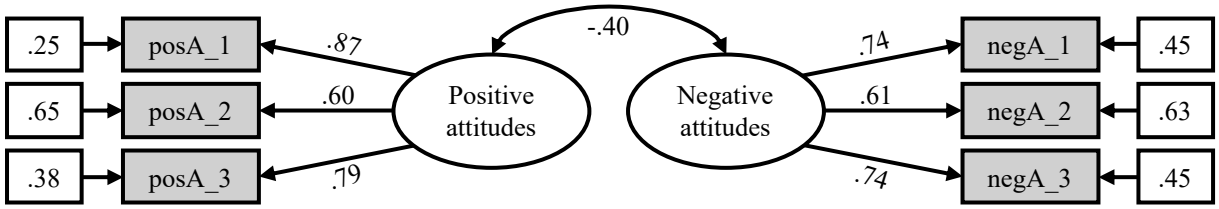
The subjectively perceived AI literacy (AILit), AI self-efficacy (AISEff) and AI self-competency (AISCom) of the teacher trainees were assessed using the Meta AI literacy scale (MAILS, Carolus et al., 2023). The 30 items are each rated on an eleven-point rating scale (not at all pronounced 0 – 10 very well pronounced). The scale is multidimensional. The AILit factor is composed of the factors use & apply AI (UsApAI, 6 items, $\alpha = 0.96$), know & understand AI (KnUnAI, 6 items, $\alpha = 0.88$), detect AI (DetAI, 3 items, $\alpha = 0.84$) and AI ethics (AIEth, 3 items, $\alpha = 0.87$). The factor AISEff is formed from the subcategories AI problem solving (3 items, $\alpha = 0.90$) and AI learning (3 items, $\alpha = 0.88$). The AISCom factor is composed of AI persuasion literacy (3 items, $\alpha = 0.73$) and AI emotion regulation (3 items, $\alpha = 0.83$). The reliabilities for each construct are in the acceptable to very good range.

Modelling

According to the multi-component model of attitude (Zanna & Rempel, 2008), a person's attitude is derived from the overall evaluation of cognitive, affective, and behavioural information. Attitudes can be ambivalent, i.e. both positive and negative (Haddock & Maio, 2014). For example, on a cognitive level, a person may perceive a technology as useful and yet at the same

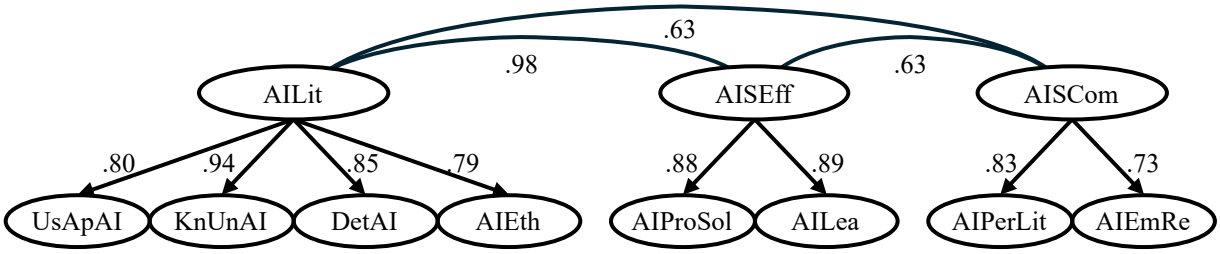
time recognise risks in its use (e.g. data protection). On an affective level, both positive emotions (e.g. joy) and negative emotions (e.g. frustration) can arise when the use of a technology leads to successes but also failures. On a behavioural level, a person may consciously reject the use of a technology in certain situations (e.g. sensitive data) despite an overall high willingness to use it. Against this background, the positive and negative attitudes of teacher trainees were modelled as two separate and mutually influencing factors using confirmatory factor analysis (see Figure 2). Both the fit indices (CFI = 0.998, RMSEA = 0.020, SRMR = 0.025) and the non-significant chi-square test ($\chi^2(8) = 9.325$, p=.316) indicate a very good fit of the model (Hu & Bentler, 1999; MacCallum et al., 1996).

Figure 2. Latent measurement model of positive and negative attitudes.



Based on the multidimensional approach of Carolus et al. (2023), the constructs AILit, AISEff, and AISCom were specified as latent variables using confirmatory factor analysis (Figure 3). Although the chi-square test is significant (χ^2 (381) = 781.309, p<.001), which is often observed in larger samples and complex models, the fit indices (CFI = 0.953, RMSEA = 0.048, SRMR = 0.053) indicate a good model fit (Hu & Bentler, 1999; MacCallum et al., 1996).

Figure 3. Latent measurement model for AILit, AISEff, and AISCom.



Results

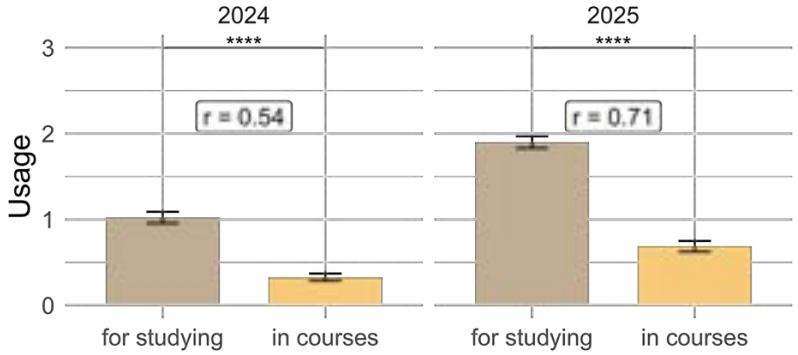
In 2024, the majority of students (74.5%) stated that generative AI is never used in courses. Only a small proportion of respondents answered that they rarely (19.1%), occasionally (5.5%), or regularly (0.9%) used AI. However, the frequency of use increased in 2025. More students stated that AI tools are used rarely (23.9%), occasionally (16.4%), or even regularly (4.0%) in courses. Nonetheless, the majority of respondents still stated that AI is never used in courses (55.7%).

The frequency of study-related out-of-class AI use has also increased. In 2024, most students stated that they never (40.5%) or rarely (23.6%) used AI for study-related matters. However, a significant number of students used AI tools occasionally (29.1%) or even regularly (6.8%). In 2025, only 10.0% of students said that they never used AI tools for their studies. Most respondents indicated they used AI rarely (23.4%), occasionally (33.3%), or even regularly (33.3%) for their studies.

Paired Wilcoxon tests were used to examine the extent to which teacher trainees rated the frequency of use of generative AI for their studies and in courses differently (Figure 4). The students indicated that they used generative AI more frequently outside of class for their studies (2024: $\mu = 1.02$, SE = 0.067, Mdn = 1 | 2025: $\mu = 1.90$, SE = 0.069, Mdn = 2) than in courses (2024: $\mu = 0.33$, SE = 0.042, Mdn = 0 | 2025: $\mu = 0.69$, SE = 0.063, Mdn = 0). According to the

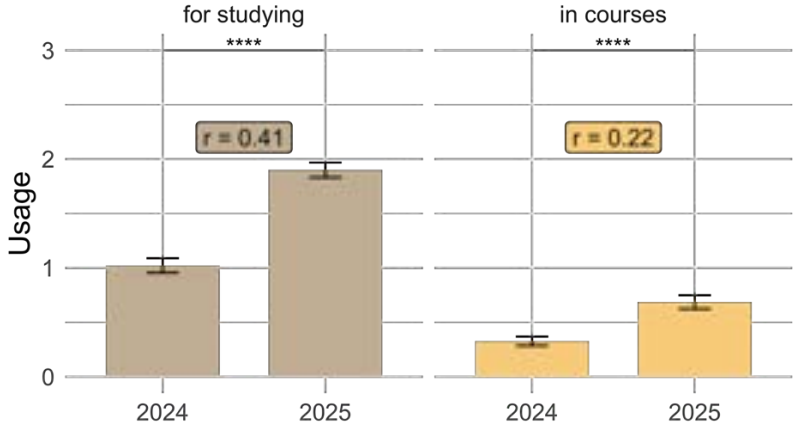
Wilcoxon rank sum test, this difference is significant in both surveys, with a large effect size in each case (2024: V = 7196, p < .001, r = .54 | 2025: V = 11753, p < .001, r = 0.71).

Figure 4. Comparison of frequency of out-of-course use and use in courses.



To analyse the changes in frequency of use, unpaired Wilcoxon rank sum tests were calculated based on statistically independent samples. It can be seen that both the study-related out-of-course use of AI (V = 12096, p < .001, r = 0.41) and in courses (V = 17408, p < .001, r = 0.22) increased significantly over time with a medium or small effect size (Figure 5).

Figure 5. Comparison of the frequency of generative AI use in 2024 and 2025.



To examine the relationship between attitudes and the frequency of use reported by students (Figure 6), linear regressions were calculated based on data from both surveys. There is a significant correlation between positive attitudes and frequency of use (b = 0.45, SE = 0.04, t = 12.58, p < .001), i.e. students who report higher usage tend to have more positive attitudes. Frequency of use explains 27% of the variance in positive attitudes ($R^2 = 0.27$). Negative attitudes also show a significant correlation with frequency of use (b = -0.14, SE = 0.03, t = -4.08, p < .001), i.e. students with higher usage rates have fewer negative attitudes towards the technology. However, the explained variance is significantly lower at $R^2 = 0.04$ compared to positive attitudes.

A multivariate analysis of variance was calculated to compare the attitudes of students in 2024 and 2025 (Figure 7). The attitudes differ significantly with a medium effect size ($\Lambda = .94$, $F(2 , 418) = 13.95$, $p < .001$, $\eta^2 = 0.06$). In the follow-up tests, t-tests with Bonferroni correction were calculated for the positive and negative attitudes. The positive attitudes of the students grew significantly from 2024 ($\mu = -0.177$, SE = 0.061) to 2025 ($\mu = 0.225$, SE = 0.063) with a small to medium effect size (t(419) = -4.57, p < .001, d = -0.45). The negative attitudes towards AI among students did not change significantly between 2024 ($\mu = -0.009$, SE = 0.056) and 2025 ($\mu = -0.002$, SE = 0.053) (t(419) = -0.09, p = .93, d < -0.01).

Figure 6. Mean values of attitudes with standard errors in relation to the frequency of use.

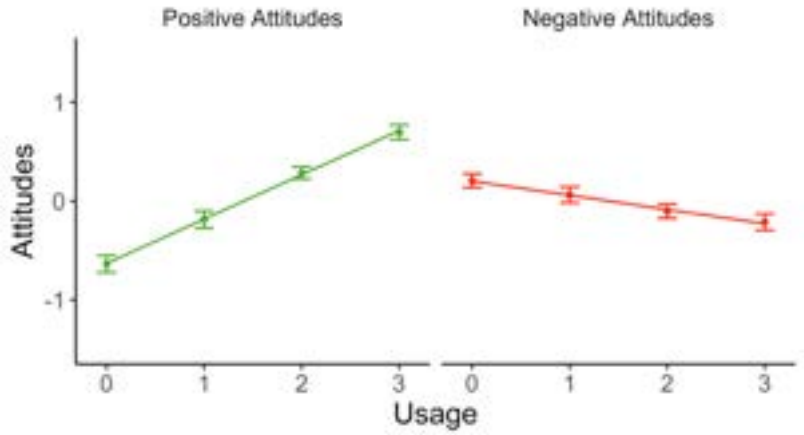
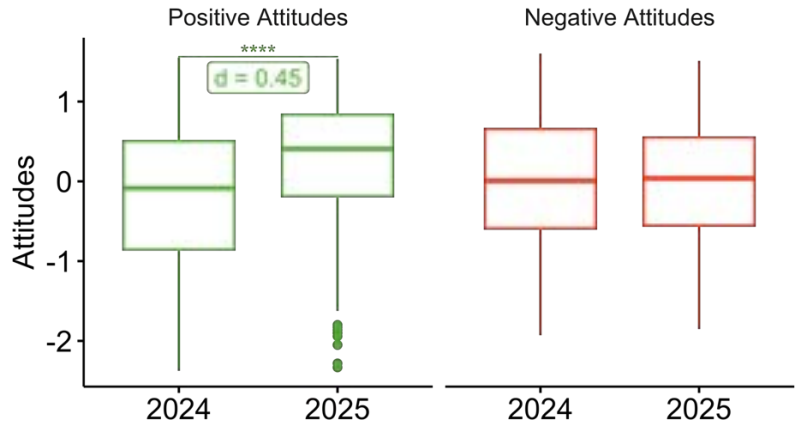
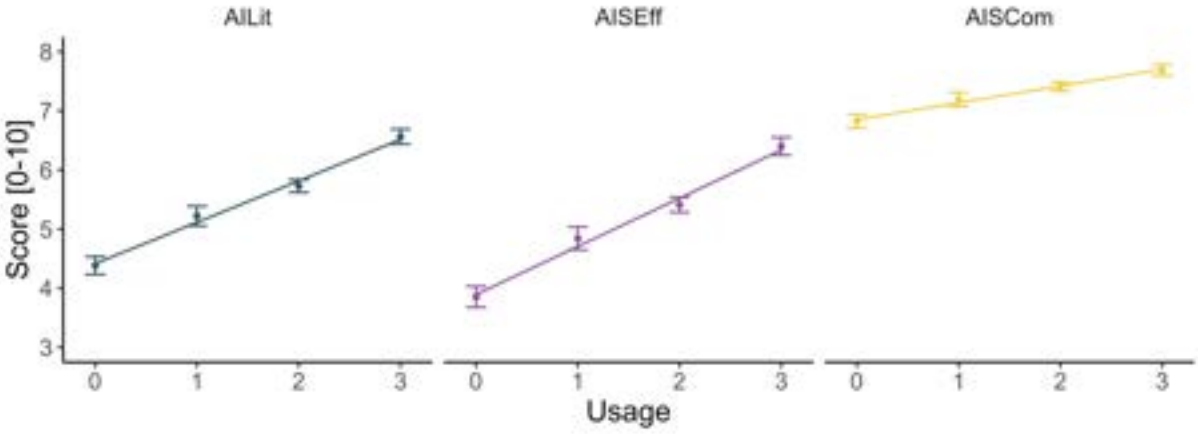


Figure 7. Comparison of attitudes towards generative AI in 2024 and 2025.



As with the attitudes, the correlations between frequency of use and AI literacy, AI self-efficacy and AI self-competence (Figure 8) were examined using linear regression analyses. All data from the surveys were used for this purpose. All factors showed a significant correlation with frequency of use (AILit: $b = 0.70$, $SE = 0.06$, $t = 10.86$, $p < .001$ | AISEff: $b = 0.81$, $SE = 0.08$, $t = 10.77$, $p < .001$ | AISCom: $b = 0.28$, $SE = 0.05$, $t = 5.92$, $p < .001$). The variance explained by usage behaviour is $R^2 = 0.22$ (AILit), $R^2 = 0.21$ (AISEff), and $R^2 = 0.08$ (AISCom).

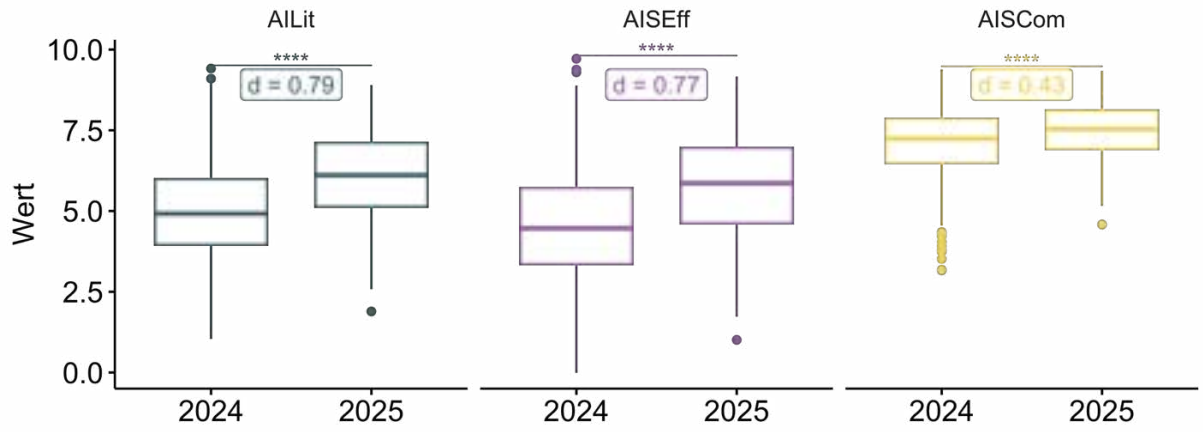
Figure 8. Correlation between the perceived AI competences and the frequency of use.



In a final study, the students' perceived competence in 2024 and 2025 (Figure 9) was compared. For this purpose, a multivariate analysis of variance with Pillai's Trace was calculated, as the significant results of the Levene tests (AILit: $F(1, 419) = 6.63$, $p = .01$ | SCom: $F(1, 419) = 8.43$, $p < 0.01$ | SEff: $F(1, 419) = 6.35$, $p = .01$), showed no variance homogeneity between the groups.

The analysis shows that the students' perceptions of competence differ significantly between years with a large effect size ($V = 0.15$, $F(3, 417) = 24.52$, $p < .001$, $\eta_p^2 = 0.15$). Welch's tests with Bonferroni correction were performed for each variable to analyse this effect in more detail. A comparison of the students' AI literacy ratings reveals a significant difference between the years 2024 ($\mu = 4.86$, $SE = 0.11$) and 2025 ($\mu = 6.04$, $SE = 0.09$) with a medium to large effect size ($t(410) = -8.14$, $p < .001$, $d = 0.79$). A similar picture emerges when comparing the AI self-efficacy ratings, which were lower on average in 2024 ($\mu = 4.42$, $SE = 0.13$) than in 2025 ($\mu = 5.77$, $SE = 0.11$). This difference is significant with a medium to large effect size ($t(412) = -7.97$, $p < .001$, $d = 0.77$). The AI self-competence rating also increased significantly from 2024 ($\mu = 7.04$, $SE = 0.08$) to 2025 ($\mu = 7.50$, $SE = 0.06$) with a small to medium effect size ($t(399) = -4.42$, $p < .001$, $d = 0.43$).

Figure 9. Comparison of perceived AI competences in 2024 and 2025.



Discussion

The results of this study show that the use of generative AI in teacher training has increased and that the majority of students now use this technology occasionally or regularly for their studies. Even though the use of AI tools in courses has increased significantly, this technology is still not used in most courses. The results of the study show that generative AI is used significantly more often outside of courses than within courses. Thus, hypotheses H1.1 and H3.1 can be confirmed.

In the context of this study, increased use of generative AI is associated with more positive attitudes and fewer negative attitudes. Hypothesis H2.1 can thus be confirmed. However, it is striking that the correlation between use and positive attitudes is significantly stronger than the correlation between use and negative attitudes. This suggests that experiences primarily contribute to the perception of potential, while concerns and perceptions of risk only decrease slightly. This effect is also evident when comparing the attitudes of students in 2024 and 2025. With increased usage in 2025, there is also an increase in positive attitudes among students, while negative attitudes remain unchanged. Hypothesis H3.2 can therefore only be accepted to a limited extent for positive attitudes.

There is a positive correlation between frequency of use and the level of AI literacy, AI self-efficacy, and AI self-competence. Hypothesis H2.2 can therefore be confirmed. Students' experience with generative AI leads to greater confidence in their own abilities and the perception that they can use AI in a targeted manner. However, it should be noted that this study deals with subjectively perceived competencies. Frequent use can therefore also lead to a misjudgement of competence, especially if students accept the information generated by AI without systematic verification. This is particularly relevant in the case of generative AI, because the technology produces outputs that are written in a convincing manner but often incorrect in terms of content.

It therefore remains unclear to what extent the increased perceptions of competence are actually accompanied by objective gains in competence. A comparison of students' perceptions of competence between 2024 and 2025 also shows a significant increase in the perception of competence in all categories considered; hypothesis H3.3 can thus be accepted.

Limitations Of The Study

Despite the meaningful results, some limitations must be taken into account. For example, the frequency of use is recording through single-item measurements, which limits the objectivity and differentiation of the measurement. Furthermore, the data is cross-sectional, which reflects differences between the survey dates in 2024 and 2025, but does not allow conclusions to be drawn about individual changes. Finally, the measurement of skills was based exclusively on self-assessments and not on skills tests. The extent to which experience with generative AI influences actual skills development cannot be answered within the scope of this study.

Conclusion

Overall, the results of this study show that the use of generative AI in teacher training has increased significantly within a short period of time. While students are developing more positive attitudes towards the technology and rate their AI literacy, AI self-efficacy, and AI self-competence higher, negative attitudes remain unchanged. In addition, the use of generative AI in courses has been limited so far, with students primarily using AI outside of institutional learning settings. On the one hand, this indicates an increasing normalisation of generative AI in everyday student life, but on the other hand, it also shows that this development has so far been largely self-organised and less supported by universities in a targeted manner. Thus, it becomes clear that although increasing use is an important foundation, it does not automatically lead to pedagogically and didactically reflective application in later careers. In order for teacher trainees to be prepared for the use of generative AI in a school context, more than just user experience is needed. They must develop the skills to use AI responsibly, didactically, and reflectively. At this point, the university has a central responsibility to prepare future teachers for this task. The work of (Damköhler et al., 2024a, 2024b, 2025) or Herz et al. (2025) shows how generative AI can be successfully implemented in teaching.

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Augmented Reality For Chemistry Education: Visualizing The Invisible In The Nitrogen Biogeochemical Cycle – A Pilot Study

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Chemistry is a subject that students usually find very complex, also due to the triple nature of chemical concepts. Learners have to bridge, in their working memories, different levels of chemical phenomena explanations in order to adequately understand them. These learning processes can cause difficulties. One way to address these difficulties is through the use of technology. Virtual learning environments, such as augmented reality (AR) can provide important information, enable connections between observable (macroscopic) and unobservable (submicroscopic) processes and thereby might contribute to a better understanding of chemistry. The aim of this pilot study was to gain insight into pre-service primary school teachers' attitudes toward the use of AR technology in the context of environmental chemistry and sustainable development as well as their perceptions of the usability of the AR application. 10 participants completed the Technology Acceptance Model questionnaire and the System Usability Scale. The results showed that the pre-service teachers had positive attitudes toward AR technology, perceived the AR application easy to use, and expressed willingness to participate in additional courses that integrate AR into chemistry teaching and learning. These findings primarily indicate the feasibility and acceptance of AR supported laboratory activities in environmental chemistry. The results provide a foundation for further research examining the effects of AR on conceptual understanding, particularly in relation to supporting connections between macroscopic, submicroscopic and symbolic representations of chemical phenomena.

Keywords: augmented reality, environmental chemistry, pre-service teachers

Introduction

In science education, assessing students' conceptual understanding is essential for enhancing learning outcomes (Halloun & Hestenes, 1985). It is well known that students experience difficulties in constructing and understanding of chemical concepts (Johnstone, 1991). Previous research (Horvat et al., 2023; Tan et al., 2020) has highlighted the importance of conceptual understanding in science education. Therefore, it is crucial for learners to develop deep comprehension of scientific ideas, rather than merely memorizing facts. The learning difficulties students face in different science subjects should be taken into account when planning instructional approaches (Taber, 2008). To identify these difficulties and address them effectively, an understanding of both the discipline and the philosophy of chemistry is required (Kaya & Erduran, 2013). Consequently, chemistry educators need to be familiar with the nature of chemical phenomena, not only with the chemistry content they teach (Erduran, 2007). However, previous studies (Allen et al., 2024; Pavlin et al., 2009; Syahrial et al., 2023) have shown that primary school and chemistry teachers often hold misconceptions about various chemistry topics. These findings suggest that pre-service teachers in particular possess significant gaps in their conceptual chemistry content (Allen et al., 2024).

The major source of complexity in chemistry lies in the nature of chemical concepts, which often extend beyond human senses (Johnstone, 1991). To explain chemical phenomena effectively, learners must be able to bridge different levels of chemical phenomena (Sjöström et al., 2020). Johnstone (1991) proposed a model consisting of three different levels of chemical presentations (microscopic, submicroscopic and symbolic), which is reflecting the triple nature of chemical

phenomena. Integrating all three levels of representations is essential for effective chemistry teaching (Sjöström et al., 2020) and can be supported through laboratory work (Gurung & Gurung, 2023). Due to its inherent complexity, chemistry concepts have been challenging for both learners and educators (Wilsson & Bernie, 1999). Nevertheless these challenges can be mitigated through the use of technology, which can enhance students' motivation and support conceptual understanding by providing meaningful visualizations and information (Mei-Hung et al., 2018). Emerging technology with considerable potential for chemistry education is augmented reality (AR) (Akçayir & Akçayir, 2017). Several studies have investigated the use of AR in chemistry teaching (Coduto et al., 2023; Tarng et al., 2021; Yamtinah et al., 2023). However, no previous studies have examined the use of AR to enhance students' understanding of the triple nature of chemical phenomena within the context of environmental chemistry.

Chemistry Triplet

Students often perceive chemistry as a difficult subject, due to the triple nature of chemical phenomena (Johnstone, 1991). Achieving an adequate understanding of chemical phenomena, requires learners to comprehend chemical concepts across different levels of representation. This implies that educators themselves need a thorough understanding of how chemical phenomena are represented and how the use of visual representations can support chemistry learning (Gilbert & Treagust, 2009). Johnstone (1982) who proposed that chemical phenomena can be understood at three distinct levels:

(1) Descriptive and functional: The level at which phenomena are directly experienced through the senses and can be described.

(2) Representational: The level at which symbols are used to represent entities and processes that cannot directly be observed.

(3) Explanatory: The level at which phenomena are explained using models.

In later work (Johnstone, 1991) clarified these levels as the macroscopic level, referring to observable phenomena, symbolic level which includes chemical equations, formulas and mathematical representations and submicroscopic level, which involves models of particles and interactions. Experts in chemistry are able to operate fluently across all three levels, whereas novice learners tend to function primarily at the macroscopic level and experience difficulties in relating it to the submicroscopic and symbolic levels (Talanquer, 2010). Research has shown the integrating all three levels of representation, particularly through the use of interactive visualization tools can lead to improved conceptual understanding of chemistry content (Ferk Savec et al., 2009). Despite this, chemical educators often emphasizes only one level of representation at a time, most commonly the symbolic level, which can hinder students' ability to construct coherent mental models of chemical phenomena (Sjöström et al. 2020). To bridge this gap, the use of interactive visualization elements is particularly important (Wu et al., 2001). Two-dimensional and three-dimensional visualizations, such as diagrams, molecular models, and animations are commonly used as visualization tools in chemistry education (Atkins et al., 1995; McMurry & McFay, 2001). These representations function as analogue models of chemical phenomena, helping learners to connect abstract concepts with observable effects (Harrison & Treagust, 1998).

The use of emerging technologies has the potential to further address difficulties associated with understanding abstract chemical concepts (Winkellman et al., 2017). In particular, virtual learning environments enable students to explore processes that cannot be observed with the naked eye (De Jong et al., 2013). During learning chemistry, a substantial portion of information is processed through visual channels (Sanders & McCormick, 1987), These channels can be

effectively supported through virtual technologies that provide real-time visualization, three-dimensional representations and opportunities for learners to manipulate and interact with virtual or real objects.

Augmented Reality

Augmented reality (AR) is a virtual learning environment that enables the digital enrichment of learning content through interactive experiences by overlaying the computer-generated elements onto the real world. Unlike virtual reality, which fully immerse users in a simulated environment, AR enhances real world without completely replacing it (Ardiny & Khanmirza, 2018). Azuma (1997) defined AR as technology that fulfils three main criteria: (1) it combines real and virtual environments, (2) it is interactive in real time and (3) it is registered in three-dimensional space. Accordingly, AR represents the continuum between the real and the virtual world (Milgram et al., 1994). In chemistry education, AR technology allows the visualization of abstract chemical phenomena particularly at a submicroscopic level of representation (Mazzuco et al., 2022). AR applications have been developed across all educational levels (Bacca et al., 2019), and studies indicate that AR can enhance students' learning outcomes (Tarng et al., 2022). However, the effectiveness of AR is influenced by multiple factors, including technology acceptance (Liu et al., 2022). Inappropriate use of AR applications may hinder learning. Making it essential to evaluate the usability and suitability of each application within its specific learning context (Peeters, 2022). The effectiveness of an AR application in the learning process can be assessed based on three criteria: (1) effectiveness, that is, whether it enables task completion and the attainment of high-quality outcomes; (2) efficiency, meaning that it requires minimal resources for its use; and whether it provides; and (3) user satisfaction, that is whether it is engaging and motivating for learners (Brooke, 1995). Ribič and Devetak (2024) highlighted in their literature review that no previous studies have investigated the effectiveness of AR in supporting students' understanding of the chemical triplet. Furthermore, AR has not been previously used to linked selected chemical processes demonstrated in a laboratory setting to the context of environmental chemistry. Nonetheless, studies included in this review emphasized that ease of use and acceptance of technology are critical factors influencing the learning experience with AR. The authors also noted the lack of research on the application of AR specifically within the field of environmental chemistry.

Aim of the Research

Despite the potential of AR use to enhance chemistry learning, pre-service primary school teachers often hold misconceptions about both the triple nature of chemical phenomena (Pavlin et al., 2009), and the biogeochemical cycles of the elements, which are fundamental for understanding environmental chemistry (Ribič et al., 2025). Effective chemistry teaching can also be hindered by the lack of appropriate learning models and instructional resources (Timilsena, 2022). Previous studies have shown that AR technology can improve students' understanding of chemical concepts by providing interactive visualizations that support learning at submicroscopic and symbolic levels (Tarng, 2022; Tsai et al., 2021). However, the effectiveness of AR-based learning depends on multiple factors, including learners' acceptance of the technology (Tarng, 2022) and the usability of the application (Peeters et al., 2022). Laboratory work has been shown to further support students' understanding of chemical phenomena by allowing observation of processes at the macroscopic level. Integrating AR with laboratory activities therefore provides an opportunity to bridge the gap between observable phenomena and abstract chemical representations, offering learners information that cannot be directly observed with the naked eye. Based on this rationale, the aim of this pilot study was to evaluate pre-service primary school

teachers' technology acceptance and perceptions of the usability of an AR application designed to enhance learning during laboratory work in environmental chemistry. Specifically, the study addressed the following research questions:

(1) What is the attitude of pre-service primary school teachers towards the use of AR in the implementation of the environmental chemistry learning module?

(2) How do the pre-service primary school teachers perceive usability of the AR application?

Participants

A total of 10 undergraduate second year pre-service primary school teachers (20 years old) from the Faculty of Education at the University of Ljubljana participated in this pilot study.

Instruments

Two paper-based questionnaires were used to collect the data in this study. The System Usability Scale (SUS) by Brooke (1996) was employed to evaluate the usability of the AR application within the environmental chemistry module. The SUS questionnaire is widely used tool for assessing usability, perceived usefulness, user attitude, intention to use and perceived ease of use. Responses were recorded on a 5-point Likert-type scale ranging from 1 (*strongly disagree*) to 5 (*strongly agree*). For positively formulated items responses of 3 or higher were considered positive feedback, whereas for negatively formulated items, responses of 3 or lower were treated as positive feedback (see Table 1).

The Technology Acceptance Questionnaire (TAM) by Holden & Rada (2014) was used to investigate participants' acceptance of the AR system when learning specific chemical phenomena. The questionnaire included 15 items assessing three dimensions: perceived ease of use (PEU), perceived ease of use and usability (PEUU) and perceived usefulness (PU). Responses were recorded on a 7-point Likert-type scale ranging from 0 (strongly disagree) to 6 (strongly agree). In addition, five items using semantic differential scale ranging from 1 (*bad*) to 7 (*good*) were included to assess participants' attitudes toward the use of the technology (AT).

Research Design

This pilot study introduced a new environmental chemistry module on the nitrogen cycle to pre-service primary school teachers. The module included ten different activities, a relatively large number intended to provide participants with broader contextual knowledge of nitrogen cycling across different environmental spheres. Four of these activities were laboratory activities enhanced with AR visualizations: (1) the simulation of the Haber-Bosh process, (2) the dissolving of ammonia in water (the fountain), (3) spectrometry to determine the concentration of ammonium ions in water, and (4) the adsorption of ammonium and nitrate ions on soil particles. These AR visualizations represented processes at the submicroscopic level, providing learners with interactive, otherwise unobservable views of chemical phenomena. Prior to the module, participants attended a 10-minute training session to familiarize themselves with the AR technology and associated hardware. After completing the module, participants fulfilled paper-based questionnaires (SUS and TAM). For reporting purposes, the items measuring perceived ease of use (PEU) and perceived ease of use and usability (PEUU) were combined into a single category (PEU+PEUU). Given the small sample size, a descriptive approach was used to analyse the data.

Findings and Discussion

The multimedia environment was evaluated using two instruments. In this pilot study, the primary aim of the SUS was to assess the usability of the AR app and to determine its suitability for the

implementation in the main study. Overall, participants evaluated the AR application positively, indicating that it was easy to use and supportive of the learning process (*Table 1*).

Table 1. Students' evaluation of the items in the SUS instrument.

Category	No. of items evaluated as good	No. of items evaluated as neutral	No. of items evaluated as poor	Total No. of items
Usability	5	3	0	8
Perceived usefulness	2	0	0	2
Attitude	2	2	0	4
Intension to use	2	1	0	3
Perceived ease of use	2	1	0	3
Total number of items				20

Based on participants' responses across all SUS categories, the AR application demonstrated good overall usability. The students reported positive attitudes toward the use of AR in chemistry learning, expressed willingness to attend additional classes using this technology, and perceived the application easy to use and easy to learn. These findings are consistent with previous studies (Peeters et al., 2022; Akçayir & Akçayir, 2017), which have shown that well-designed AR applications can positively influence students' usability perceptions and learning experiences. From a usability perspective, Brooke (1995) emphasized that effective system should enable task completion, require minimal resources for use and provide satisfying user experience. The results of this study suggest that the developed AR application meets these criteria, as participants found it engaging, motivating and supportive during laboratory work. This is particularly important in chemistry education, where visualization tools are needed to support the integration of macroscopic observations with submicroscopic representations (Gilbert & Treagust, 2009; Johnstone, 1991). However, these findings should be interpreted with caution as this was a pilot study and participants were exposed to AR for the first time. The positive evaluations may be partially influenced by a novelty effect, whereby learners initially respond more favourably to new and unfamiliar technologies (Mazzuco et al., 2022). Consequently, while the current results indicate that the AR application is usable and well accepted, further investigation in a larger scale study is required to evaluate its long-term impact on learning and conceptual understanding.

Results of questions on questionnaire on technology acceptance are presented in *Table 2*.

Table 2. Descriptive results of technology acceptance factors (TAM)

TAM dimension	No. of items	Mean range	Interpretation*
PEU + PEUU (Perceived Ease of Use & Usability)	9	5.3 – 6.6	High
PU (Perceived Usefulness)	5	5.6 – 6.8	High
AT (Attention to Use)	5	3.2 – 6.9	Mainly positive

*Interpretation is based on item mean scores relative to the scale midpoint. Scores above the midpoint are interpreted as positive (Liu et al., 2022).

As shown in *Table 2*, participants responses indicated mainly positive perceptions across all TAM factors. No student reported neutral or negative ratings for any statement related to technology acceptance, suggesting that the AR application did not negatively affect students' engagement

with or understanding of the learning content (Tarng et al., 2022). These results suggest that the AR application was generally well received. The high PEU + PEUU scores indicate that the students found the system easy to use and supportive of learning, while the high PU scores demonstrate that learners recognized its educational value. The AT scores, although slightly lower for one item, indicate that most participants were willing to engage with the AR application in future learning activities. From a theoretical perspective, the positive usability and technology acceptance results suggest that AR has the potential to support learners in bridging the gap between macroscopic observations and submicroscopic or symbolic representations in chemistry, consistent with the chemical triplet framework (Johnstone, 1991; Gilbert & Treagust, 2009). By providing visualizations of the processes such as the Haber-Bosch reaction, ammonia dissolution, and ion adsorption, the AR application may offer learners interactive ways to explore chemical phenomena that are otherwise difficult to observe, which could be particularly valuable in environmental chemistry education.

Conclusions

This pilot study evaluated a newly developed AR application for teaching the nitrogen cycle in an environmental chemistry module to pre-service primary school teachers. Overall, participants reported positive perceptions of usability, perceived usefulness, and attention to use. The System Usability Scale (SUS) indicated that the application was easy to use, engaging, and supportive of learning, while the Technology Acceptance Questionnaire (TAM) demonstrated that students were willing to engage with the application and recognized its educational value.

The findings suggest that the AR application is well received and has the potential to support chemistry learning, particularly in providing interactive visualizations of chemical processes that are difficult to observe directly. However, future research with a larger sample will allow examination of additional variables, such as conceptual understanding, motivation, and learning outcomes, to more fully assess the educational impact of AR in environmental chemistry. As a pilot study, these findings should be interpreted with caution. The small sample size limits generalizability. Future studies are needed to directly assess whether these visualizations improve conceptual understanding and learning outcomes. Also, previous studies on emerging technologies in education highlighted the importance of longitudinal studies to determine whether positive attitudes toward AR are sustained over time. Therefore, larger study is required to evaluate long term impact on attitudes towards AR technology.

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Beware The Slider's Range: A Design Lesson From Physics Simulation Development

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Digital simulations are a critical component of modern education, yet guidance for the many microscopic design decisions that accompany their creation is incredibly rare. During our own development of a physics simulation, our team encountered one such decision regarding the range of the sliders in the simulation. We recount how an initial 'intuitive' choice resulted in significant changes to the simulations' functionality, which ultimately overshadowed rich details of the phenomenon. From this experience, we devised a sequence of design principles for choosing slider boundaries, which includes stating learning goals, identifying necessary inclusions/exclusions, quantifying relationships, and checking maximizing/minimizing cases. Through this explication, we illuminate the utility of small-scale design principles for creating digital simulations for educational applications.

Keywords: Physics, Simulations, Design Principles

Introduction

Digital educational simulations play a key role in modern STEM education and have proved extremely effective at improving students' conceptual understanding (Rutten et al., 2012; Wieman & Perkins, 2005). Today, a wide array of such simulations exists, covering a multitude of domains and topics including physics, chemistry, and mathematics (Banda & Nzabahimana, 2021; Fan & Geelan, 2013; Molina-Toro et al., 2019; Moore et al., 2014; Yuriy et al., 2022). Given their resounding empirical support and wide applicability, developing educational simulation technologies remains a vital goal in educational research.

Although there are countless studies examining the application and effectiveness of digital simulations across disciplines, the literature on how to *create or design* such simulations remains drastically underdeveloped by comparison. There are myriad instructional design methodologies which are (in theory) generalizable, but the unique challenges presented in developing a computer-based technology mean many of these methods lack the specificity or detail to be helpful at a granular level. For example, Becker & Parker (2012) synthesized general principles from instructional and game design frameworks to develop an overarching design process for digital simulations. Their process—which follows a familiar phase-based plan with such recognizable steps as "preparation," "design," and "testing"—may offer a helpful roadmap for large-scale planning, but its limited guidance within these phases leaves designers on their own when facing the deluge of choices and commitments that must be made when building a simulation from the ground up.

Some researchers have sought to look across empirical studies which showcase digital simulations in educational environments in order to construct a sort of "best practices" list of affordances and features employed by effective simulations. Blake & Scanlon (2007) compiled one such list by comparing three simulations—two physics-based and one biology-based—and concluded that effective simulations must a) be based on real-world phenomena, b) use multiple representations like graphs and visualizations, and c) offer appropriate support and scaffolding to guide inquiry. A similar analysis by Podolefsky et al. (2010) presented a detailed case study of

two students using a physics simulation and explored how the simulation's ability to make invisible phenomena observable and provide real-time feedback contributed to the students' learning. These analyses begin to identify design priorities and goals that are specific to simulation development, but their advice still leans towards the birds-eye view—primarily considering the targets of study for simulations and the instructional environment in which they will be situated.

A larger study was performed by Scalise et al. (2011), who reviewed 79 studies of virtual labs and simulations in secondary school science classrooms. From their analysis, they composed three rubrics: one for software/hardware elements, one for the visualizations themselves, and one for the scientific inquiry which the simulation scaffolded. While many elements of their rubrics arrive at the same conclusions of the works mentioned previously (such as showing scale models of large/small phenomena or providing lesson plans), they also unpack several fine-grain components of simulation design, like API compatibility and the inclusion of auditory elements. Such atomized dissections of minute components of simulation design are quite rare and often only mentioned in passing. For instance, Podolefsky et al. (2010) did mention how the affordance of the pause button was useful for one student, but an interrogation of the simulation at that scale was obviously not their main focus.

One examination of simulation design at this grain-size is found in Williams (2003), who drew upon theories from design and learning research to critique the common practice of defaulting to interface choices which seem to be the most intuitive at first glance. Instead, Williams examines the ways in which miniscule trade-offs in modes of interaction—like swapping direct manipulation of an object with typing in a command prompt or delaying the speed at which the simulation updates or responds to user inputs—may have a subtle but significant effect on the learner's cognitive experience. While Williams still devotes substantial time to discuss larger-scale issues (like the designer's "intent"), his considerations on interface design remain one of the few instances of such zoomed-in granularity.

By far, the most detailed guidance on small-scale design choices for digital simulations comes from the Physics Education Technology group (PhET, n.d.), who have published in-depth accounts of both their approach to designing educational simulations (Adams et al., 2008b) as well as implementing them in practical settings (Adams et al., 2008a). These treatises condense results from over 200 clinical interviews of students interacting with digital simulations, and so touch on many of the themes already mentioned: real-world connections, guiding prompts, and scaffolding inquiry. In addition, Adams et al. (2008b) shed much-needed light on a variety of design choices that arise during the piece-by-piece construction of such computer simulations: default/start-up settings, stylization, color choice, distinguishing "control panels" from "play areas," and even the use of backgrounds.

One of the conclusions Adams et al. (2008) draw regarding interface design is that controls which "resemble using the mouse as a simple extension of direct manipulations by hand" (p. 568) are particularly intuitive. This philosophy of prioritizing direct manipulation in simulations has been understood for some time (Shneiderman, 1997), but Adams et al. go a step further to share at length the subtle differences they observed between users' interactions with various types of manipulatable elements, such as click-and-drag objects, radio buttons, and checkboxes. For designers new to the computer simulation landscape, deconstructions like these can prove to be an invaluable asset.

For the last three years, our research team has embarked on just such a maiden voyage into digital simulation design. Our goal has been to develop simulations for upper-division physics curricula

(Jafari Ghalehkohneh et al., 2025), a niche we feel is critically underexplored. In our nascent efforts to learn the tricks and tools of the trade, we inadvertently stumbled into a design oversight which, in hindsight, may provide a useful example for unwrapping a previously undiscussed element of simulation micro-design: the decision of what *range* to use on grabbable sliders. By recounting the factors which led to this hurdle, the turbulence it caused, and the way we corrected it, we hope to contribute to the literature on micro-scale design choices for digital simulations.

In part one of this work, we will relate the development process of our first simulation, the circumstances of our design oversight, and the impact it had on users during our pilot interviews. In part two, we will outline how we used this learning opportunity to construct a sequence of design principles for decision making in this narrow but critical element of simulation design.

Part One: Simulation And Study Context

Our research group has been developing a suite of physics simulations called PhysMath (PhysMath, n.d.), which go beyond traditional visualizations of physics phenomena to incorporate interactive equations as well. These mathematical inclusions aim to address a distressingly common finding in physics education research: students who can successfully perform mathematical tasks in physics contexts often have little to no ability to explain the purpose or meaning of such actions (Arnell, Swanson, Edwards, & Edwards, 2024; Mason & Singh, 2010; Tuminaro & Redish, 2007).

Our development team consists of individuals from three fields: physicists as content experts, computer scientists to build and program the simulations, and learning scientists to base the design in education theories and conduct user testing. Our design process begins with the physicists crafting a detailed explanation of the phenomenon, which is communicated to the computer scientists to develop a basic (functional) simulation. Then, the simulation is presented to the team for feedback to improve its aesthetics and usability. When the team feels the simulation has reached a satisfactory level of polish after several iterative refinements, the learning scientists conduct clinical interviews with volunteer students to observe their behaviour and receive user feedback.

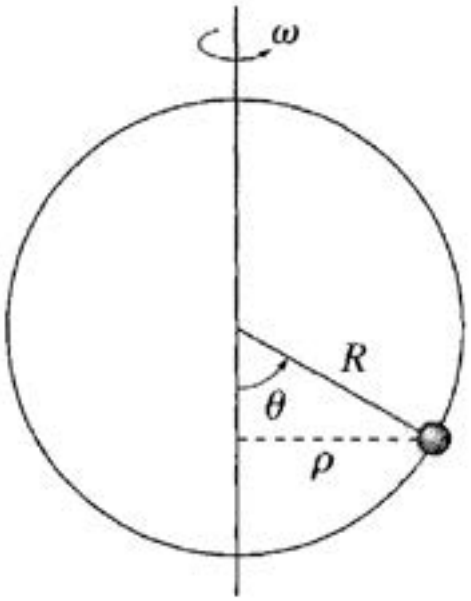
The first simulation we chose to design was the "bead on a spinning wire hoop" problem (Taylor, 2005, p. 261) from Classical Mechanics. We chose this target because it was conceptually and mathematically rich yet nearly impossible to demonstrate physically (Jafari Ghalehkohneh et al., 2025). The design experience we share in this work took place during the earliest versions of this simulation. In the following section, we will cover the necessary background for understanding the phenomenon and how a seemingly innocuous design choice on slider ranges compromised our simulation's instructional utility.

The PhysMath Bead-On-Hoop Simulation

Fortunately, a rigorous mathematical understanding of the Bead-on-Hoop is not required for our purposes in this work; instead, a cursory, qualitative explanation will suffice. For this problem, a bead is threaded onto a wire hoop with radius R, which is then spun around a vertical axis with angular velocity ω, as diagramed in Figure 1. The position of the bead at any moment can be described with a single parameter: the angle θ which the bead makes with the bottom of the hoop.

As the bead is allowed to slide around the hoop, its motion is governed by two forces. The first is gravity (traditionally symbolized by g), which always points downward and has a constant magnitude. The second force is the centrifugal force, which always points horizontally outward away from the axis of rotation and gets larger as the hoop spins faster and as the bead moves further away from the axis of rotation (a distance denoted by ρ in Figure 1).

Figure 1: The bead on a spinning hoop (Taylor, 2005, p. 261)



On its own, the gravitational force would pull the bead to the lowest point on the hoop (at $\theta = 0°$), and this is indeed the primary equilibrium point for the bead when the hoop is not spinning. As the hoop begins to spin (and if the bead is not perfectly at $\theta = 0°$), the centrifugal force will begin to grow. For small values of ω, the centrifugal force will be present but too small to overcome gravity, and the bead will continue to find equilibrium at the bottom of the hoop in spite of the hoop's rotation. But as the hoop spins faster, the centrifugal force can eventually grow strong enough to overcome gravity. When this occurs, the bead will rise away from $\theta = 0°$. As the bead approaches $\theta = \pm 90°$, the centrifugal force—although growing larger due to the increased distance ρ from the rotational axis—will approach an angle normal to the hoop, causing its influence on the bead's motion around the hoop to diminish. At the same time, the gravitational force will approach an angle which is tangential to the hoop and thus become more influential. This shifting balance will result in some 'critical angle' θ_{crit} at which the effects of gravity and the centrifugal force are equivalent, and the bead can remain stationary at this position on the hoop indefinitely; as the hoop rotates faster, the critical angle will approach 90°. Importantly, this critical angle can only exist if the centrifugal force is sufficiently strong, and so there is some 'critical angular velocity' ω_{crit} at which the hoop must spin before the bead can achieve this additional equilibrium point.

This rich bifurcation of behaviour was one of the reasons the bead-on-hoop problem was such a tantalizing target for our simulations. Our hope was that students could use the PhysMath simulation to explore how the parameters of the system—namely, the strength of gravity and the size of the hoop—would affect this critical angular velocity and observe how the motion of the bead is significantly altered as the rotation rate of the hoop crosses this crucial threshold.

As our programmers crafted the earliest versions of the PhysMath Bead-on-Hoop simulation, they followed the well-established practices for physics simulations (Adams et al., 2008b) and included draggable sliders for each of the system's parameters. Unfortunately, our team had not had any explicit discussion about what the minimum and maximum values for each slider should be. As this was the first PhysMath simulation to be built and there was no previous experience to draw upon, the programmers chose values which seemed intuitive: a minimum of 0 (0.1 for the radius slider, which cannot be 0) and a maximum of 100.

While these values may be sensible in other circumstances, they turned out to be quite problematic for the Bead-on-Hoop in particular, especially for the radius slider! The magnitude

of the centrifugal force is dependent on ρ, and thus dependent on R as well. At a radius of only a few meters, a hoop could rotate at an incredibly small rate and still create a substantial centrifugal force. This would mean that the critical angular velocity ω_{crit}—the threshold point around which we wanted our students' explorations to revolve—resides so close to zero that it practically vanishes. With the slider's maximum set at 100, even positions on the slider that would intuitively appear to be quite low (e.g., 5–10% of the slider's total length) would still represent radii that were inappropriately large and would result in an overwhelming centrifugal force.

Unfortunately, the rest of our design team did not recognize the eventual consequences of these slider ranges during our rounds of iterative feedback on the programmer's prototypes. It was only when our learning scientists sat down with students to observe their interactions with the simulation that the impact of the slider ranges was revealed. In the next section, we will share excerpts from the students' interviews to demonstrate how our design oversight hindered their explorations into the simulated phenomenon.

Pilot Study Observations

Eventually, the simulation prototype was ready for user testing. Students who were enrolled in Classical Mechanics at our institution were recruited for clinical interviews (Arnell, Swanson, Edwards, Hart, et al., 2024), in which they shared their understanding of the phenomenon and then explored the PhysMath Bead-on-Hoop simulation. On the whole, the students' experience was positive, and our observations concurred with Adams et al. (2008b) regarding the intuitiveness of controls that mimic physical manipulations. However, during these pilot interviews, we finally noticed the size of the radius slider impeding the students' learning. Here, we will share excerpts from interviews with four students: Alena, Armando, Jake, and Ronan (pseudonyms).

Alena's first act when she began exploring the simulation was to change the radius of the hoop, saying, "what happens if we make [the radius]… like, five?" As the hoop spun, the bead sat relatively stable near 90°, at which Alena commented, "It seems to just hang out right here." She then began increasing and decreasing ω, but without readjusting R to a smaller value. When this had little effect on the bead, Alena changed the bead's starting position before varying ω again. All of Alena's experiments yielded the same result: the bead found its equilibrium near 90°, regardless of any other system parameter. Alena concluded that "if you start it at the halfway mark, it will tend to stay there"—a conclusion which is only true if the hoop is spinning above the critical angular velocity.

Armando was also drawn to the radius slider first, saying "let's increase R, see what that does." He dragged the slider up about a third of the way (34 m). After watching the simulation for a moment, he moved on to other variables without resetting R. Armando played around with the sliders for gravity, friction, and angular velocity, checking the hoop's behaviour when each slider was near its minimum and maximum; in all cases, the bead's equilibrium point never shifted from the super-critical 90° position. Armando commented, "it definitely has this critical point right there, at the very side… I wonder if I increase gravity, if the position at that point changes at all?" Armando's intuition was aimed in a productive direction: a stronger-than-usual gravitational force might overpower the centrifugal force enough for him to find sub-critical behaviours. However, the influence of the absurdly large radius was so great that even when Armando slid the gravity slider to near its maximum (around 75 m/s^2), the bead's behaviour remained unchanged. Armando responded "No, it doesn't. It still stays there." In his experimenting, the only time Armando saw the bead come to rest at the bottom of the hoop was when he set ω to zero—a trivial solution, as *no* rotation results in *no* centrifugal force.

Jake took a unique approach, varying some of the last sliders on the list first; this meant he only reached the radius slider after he had already experimented with the starting position and velocity, angular velocity, and friction. Jake increased R up to around 30 m, then decreased it as he had the others. However, due to the length of the slider, Jake's 'low' value was still 8 m (giving a hoop as tall as a two-story building!). As Jake continued to experiment with the simulation, he tried removing gravity by setting g to zero. When the bead's equilibrium stayed around 90°, he remarked "it doesn't change it terribly much."

Ronan made the typical choice to interact with the radius slider first; he dragged the slider to its absolute maximum, then back to a lower value—but ultimately left it at 20m. From there, Ronan varied the gravity, friction, angular velocity, and starting position/velocity sliders. Through all his experiments, the bead maintained an equilibrium point at roughly 90°. Summing up his observations, he said "there's this side motion… it's the furthest to the side that it can be, and it just stays there."

The interviewer (first author) noticed the issue of the range slider's excessive maximum after the interviews with Alena and Armando. Unfortunately, an updated version of the simulation was not available in time for the interviews with Jake and Ronan, so the interviewer elected to not immediately intervene if the participants unwittingly set R too high. This was done to give the students an opportunity to detect the error and correct it themselves, though neither did. Eventually, the interviewer stepped in to correct the issue for Jake and Ronan once they needed to move on to the next phase of the interview.

Alena, Armando, Jake, and Ronan all shared a very similar experience during their exploration of the PhysMath Bead-on-Hoop simulation. They each increased R from its default value and performed subsequent tests while R remained at a relatively high value. In spite of their attempts at varying many of the other parameters, the bead's equilibrium at approximately 90° could not be disturbed (outside of removing the rotation of the hoop altogether). As they observed the system's behaviour, they all made comments regarding the apparent permanence of the bead's equilibrium position.

From these pilot interviews, it was immediately clear that the range of the radius slider (and possibly others) must change. Not only had the students been unable to discover any of the sub-critical behaviour examples, but they appeared to conclude from this that such behaviour may not even exist! This tendency for students to trust simulations to a fault was also observed by Adams et al. (2008a), who noticed that students may even attribute meaning to cases when simulations broke or encountered bugs, believing that the simulations *must* be portraying the phenomenon correctly.

What was far less clear to our design team was what the new slider range should be. In part two, we will share how we constructed a sequence of design principles for making such a determination—a sequence we hope will be useful for any designers who may be struggling with a similar decision.

Part Two: Design Principles For Determining Slider Ranges

For digital simulation designers who must choose upper and lower bounds for sliders representing physical parameters in a modelled phenomenon, we offer the four-stage design principle sequence we constructed from our problem-solving experience: 1) state your learning objective, 2) designate allowed/disallowed input values, 3) quantify your parameter relationships, and 4) use maximizing/minimizing cases to calculate slider boundaries.

1. State Your Learning Objectives And How They Relate To The Slider Values

As is the case with many instructional design methods (Branch, 2009), our first priority was to make our learning objectives explicit. As mentioned previously, our intent was that students who were exploring the PhysMath Bead-on-Hoop simulation should be able to find angular velocity values which were both above and below ω_{crit}, allowing them to observe and compare the differences in the bead's behaviour on either side of this threshold. To make these kinds of discoveries as natural as possible, our preference would be for ω_{crit} to fall somewhere near the middle of the angular velocity slider and remain away from the slider's edges as much as possible as the other system parameters were varied. This would increase the likelihood of users finding both categories of motion organically as they instinctively check the limits of the simulation (Adams et al, 2008a).

With this target articulated, we realized that we would need to adjust not only the scale of the radius slider which had been the apparent cause of the issue, but also the angular velocity slider so that it was scaled correctly to accommodate whatever ω_{crit} values were made possible by the values of the other system parameters. Similarly, we would also need to fine-tune the range of our gravity slider, as g affects ω_{crit} by providing a benchmark for the growing centrifugal force to overpower.

And so, our ultimate goal would be to find minimum and maximum boundaries for this trio of interconnected parameters that would restrict the possible ω_{crit} values to a reasonable range as near the middle of the angular velocity slider as we could manage.

2. Designate Specific Input Values Which Must Be Allowed/Disallowed

With the radius, gravity, and angular velocity sliders in our sights, our next step was to establish if there were any specific values for these three parameters that we must include (or exclude) for the simulation to make sense. We agreed that we must let g go to zero, as we wanted to allow students to "turn off" gravity and explore how the complete removal of that force affected the system. Congruently, we needed to allow for ω to have a minimum of zero to let students observe the (albeit trivial) cases when the hoop is not spinning and there is no centrifugal force. On the other hand, R could not be allowed to reach zero, as doing so would essentially 'break' the formulae used to calculate the bead's motion; thus, the radius slider would need a non-zero minimum value. Our final observation at this stage was that the gravity slider needed to include the value 9.8, as this is the standard g value for earth; we would then prefer that the gravity slider extend beyond that point by some amount to allow for testing gravitational forces which were stronger than earth's.

By clarifying these must-have points, we had already established the minimum for two of our three sliders, as well as getting an approximate feel for where the maximum for g and minimum for R may wind up. To find the rest of the boundaries, we would need to quantify the way changes to any one parameter would affect the others.

3. Quantify The Relationship Between Your Parameters

The relationship between the radius, gravity, and the critical angular velocity for the Bead-on-Hoop is given by Equation 1:

$$\omega_{crit}^2 = \frac{g}{R} \tag{1}$$

This expression quantifies the proportionalities we have already mentioned, and so now allows us to plug in individual values to calculate an exact critical angular velocity. By plugging in

hypothetical maximum and minimum values for g and R, we can construct a range of possible values for ω_{crit} and iteratively home in on a set of ranges for all three parameters which coincides as closely to our desired learning objectives as we can manage.

4. Use Maximizing/Minimizing Cases To Determine Slider Boundaries

Equation 1 can be looked at in two ways: trying to either maximize or minimize ω_{crit}. For our calculations, we first looked at the cases where ω_{crit} would minimize (in hindsight, if we had tried to start with the maximizing case, we would not have had enough information yet and would have resorted to the minimizing case instead).

As we had already established a minimum value of zero for the gravity slider, we began by checking how this boundary affected the possible values for ω_{crit}. Unfortunately, Equation 1 demonstrated that ω_{crit} would approach zero as g does, which means that ω_{crit} would inevitably drift to the bottom edge of the angular velocity slider regardless of the slider's overall range. While this goes against our preference to keep ω_{crit} away from the slider's edge, we realized that there would be no way to avoid this particular case without abandoning our commitment to allow g to go to zero, and so we would need to try to work around this case as best we could.

Since we could not prevent ω_{crit} from reaching zero, we elected to check what would happen at a small but non-zero value for g (we chose $g = 1$). Our calculations revealed that if we wanted to keep the minimum ω_{crit} values out of the decimals, then the absolute maximum for our radius slider would need to be 1—which speaks to why our student users were so unable to find any sub-critical behaviour with their R set so much higher! If our radius slider has a maximum of 1, then a value for g closer to the default/standard would yield $\omega_{crit} \approx 3$. This let us know that our angular velocity slider maximum shouldn't be so large as to make values in the low, single-digit range imperceptible.

With the maximum R value established, we could now look to the maximizing cases of Equation 1 to find the last of our boundaries. If we kept g at a standard value and made R smaller, then by the time we reached $R = 0.1$, ω_{crit} had already climbed to around 10. Knowing that ω_{crit} would climb even higher if g was increased as well, we felt 0.1 would be a sufficient minimum for the radius slider to keep it from pushing ω_{crit} too large.

At this point, the only boundaries we had not established were the maximums for the gravity and angular velocity sliders. As Equation 1 shows, ω_{crit} and g are directly proportional, so allowing higher values of g would continue to raise the maximum possible value for ω_{crit}. This meant the maximum values for these sliders could be as low or high as we preferred. We resolved to cap the two sliders low enough that single-digit values for ω_{crit} wouldn't be completely washed out, and so chose 20 for a maximum ω and 25 for a maximum g (though these values could have been slightly different and the overall functionality of the simulation would remain relatively unchanged). These particular values meant that the maximum possible ω_{crit} would be around 16, which we felt would keep ω_{crit} acceptably far away from the top edge of the angular velocity slider in most cases.

Conclusion

In this work, we have shared an account of a challenge our research team encountered while designing a physics simulation: due to the interdisciplinary nature of the task, our programmers chose values for the range of our simulation's parameters sliders which were ill-suited for the modelled phenomenon. When this oversight was not noticed by our team's physicists and learning scientists, we conducted pilot interviews in which the improper slider ranges had a significant impact on the students' exploratory sessions with the simulation. Learning from this

mistake, we have since generated a sequence of design principles to help other designers calculate optimal slider ranges for their own educational simulations. This sequence asks designers to articulate their learning objectives, designate necessary input values, quantify their parameter relationships, and using maximal/minimal cases to arrive at slider ranges based on concrete justifications.

Through this experience, our team came to appreciate how minor details in interface design can have a substantial effect on the utility of educational simulations—especially when modelling complex phenomena. While there are simulation design teams which have been open about sharing their own design lessons (Adams et al., 2008a; 2008b), the fine-grain operationalization of design choices for computer-based simulations could use substantially more explication. We hope our detailed deconstruction and analysis of the process and rationalization behind one micro-design choice can assist other educational simulation designers when faced with the same conundrum. Furthermore, we encourage the publication of similar micro-design deconstructions to illuminate the otherwise imperceptible challenges presented by digital simulation design.

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What Factors Influence Pre-Service Science Teachers' Ethical Use Of ChatGPT?

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This study examines factors influencing pre-service science teachers' ethical use of ChatGPT using the Theory of Reasoned Goal Pursuit (TRGP). Through directed content analysis of responses from 28 students, key determinants related to procurement goal beliefs, approval goal beliefs, attitudes, subjective norms, motivation, and perceived behavioural control are identified. The findings offer insights into how these constructs shape ethical engagement with ChatGPT, highlighting the need for targeted interventions to foster responsible use in education

Keywords: ChatGPT, academic integrity, pre-service teachers

Introduction

Large language models (LLMs), such as ChatGPT, are significantly reshaping how students approach academic tasks (Kikalishvili, 2023). These tools assist in developing teaching units, rubrics, and quizzes (Cooper, 2023). The growth of these models also relates to increased academic dishonesty and plagiarism (Kasneci et al., 2023; Milano et al., 2023). Recent studies confirm these trends in educational settings (Toma & Yánez-Pérez, 2025). There is a clear need to investigate factors influencing ethical use.

Against this background, this study applies the Theory of Reasoned Goal Pursuit (TRGP) to explore determinants of ethical ChatGPT use (Ajzen & Kruglanski, 2019). The TRGP connects personal goals with social and environmental beliefs, which could position this framework as useful in explaining how students use LLM. The model suggests that behaviour results from the interaction between desired outcomes and perceived pressures. Therefore, the study examines proactive ethical use of LLM rather than just misuse. Specifically, the study aims to identify factors that foster ethical use during professional development. Therefore, it does not focus on predicting academic misconduct. In doing so, finding might inform design of professional development programs focused on fostering an ethical use of LLM like ChatGPT. Indeed, understanding these factors is necessary for teacher education programs. Pre-service teachers must learn to balance efficiency with academic standards. The results of this study can guide policy making within universities. This study addressed the following research question:

- What factors drive the ethical use of ChatGPT?

Theoretical Underpinnings

The TRGP is a recently developed comprehensive framework designed to predict and modify behaviours (Ajzen & Kruglanski, 2019). It integrates components from Ajzen's (1991) Theory of Planned Behaviour (TPB) and Kruglanski et al.'s (2002) Goal Systems Theory (GST) to incorporate the influence of individuals' goals. TRGP proposes that behaviours are primarily driven by two types of goals: (1) procurement goal beliefs and (2) approval goal beliefs. Procurement goal beliefs refer to the desired outcomes individuals aim to achieve through their behaviour, serving as determinants of attitudes. Approval goal beliefs, in contrast, represent the significant others whose approval individuals seek by performing the behaviour, acting as antecedents of subjective norms.

The theory suggests that procurement goal beliefs exert a stronger influence on attitudes than behavioural beliefs, while approval goal beliefs have a greater impact on subjective norms than normative beliefs. Consequently, individuals are more likely to adopt a behaviour if it aligns with both procurement and approval goals. For example, students may aim to complete university assignments efficiently (procurement goal) and gain peer approval (approval goal). Positive beliefs about ChatGPT, such as improved understanding of material, may not motivate its use if procurement goals remain unmet. Similarly, normative beliefs regarding individuals whose approval is not sought, such as professors, may not significantly influence behaviour.

The theory also posits that attitudes and subjective norms form the foundation for motivation to engage in a behaviour. Within this framework, motivation is defined as "a strong desire to perform the behaviour" (Ajzen & Kruglanski, 2019, p. 775). Higher levels of motivation are expected to lead to the formation of intentions, which subsequently predict and influence behaviour. Additionally, perceived behavioural control moderates' motivation and also directly affects intentions. For instance, pre-service teachers with positive attitudes toward the ethical use of ChatGPT and strong subjective norms will exhibit greater motivation to use ChatGPT ethically. This motivation is further strengthened and moderated by high levels of perceived behavioural control over the behaviour.

Methodology

Participants

Participants were selected using purposive sampling to ensure experience with ChatGPT's ethical use (Cohen et al., 2018). Recruitment criteria included: (1) undergraduate status, (2) attendance in an in-person course, (3) willingness to create a ChatGPT account and participate, and (4) extensive experience in ethical ChatGPT use.

Eligible students completed an intervention on ethical ChatGPT use for teaching science (Toma & Yánez-Pérez, 2024). Of 37 first-year teaching students recruited, nine were excluded: six did not meet the attendance criterion, and three failed the experience criterion. The final sample included 28 students (89.3% female, mean age = 21.93, SD = 1.80). For university entrance, most pursued social sciences (67.9%), with others in science (17.9%) or vocational training (14.3%). Participants completed an elicitation questionnaire post-intervention.

Data Collection Instrument

An elicitation questionnaire, following standardized protocols (Fishbein & Ajzen, 2010), included eight open-ended questions. Participants were first provided a definition of ethical ChatGPT use: "Ethical use involves seeking information, clarifying concepts, or generating ideas for inspiration, as done in this course. Fraudulent use includes copying ChatGPT content or having it complete assignments".

Participants listed their most salient procurement goal beliefs ('What is the most important personal goal you could achieve by using ChatGPT ethically this semester?') and approval goal beliefs ('Would you use ChatGPT ethically to gain approval from specific individuals or groups? List them.'). They then identified advantages and disadvantages of ethical ChatGPT use ('What are the advantages and disadvantages of using ChatGPT ethically this semester?'). Normative beliefs were elicited by listing individuals or groups who would approve or disapprove of their ethical use ('Who would approve or disapprove of your ethical use of ChatGPT this semester?'). Finally, control beliefs were identified by listing factors facilitating or hindering ethical use ('What factors would make it easier or harder to use ChatGPT ethically this semester?').

Data Analysis

Directed content analysis was employed to analyse students' responses based on predefined TRGP belief categories (Cohen et al., 2018). Guided by theory, two researchers independently coded responses into categories: personal goals, positive/negative behavioural beliefs, approval-seeking individuals, approval/disapproval normative influences, and facilitating/hindering control beliefs. Inter-rater agreement exceeded 80%, indicating high consistency. Discrepancies were resolved through discussion until consensus was achieved. Modal salient beliefs—determinants of ethical use—were identified using frequency counts, retaining those mentioned by at least 30% of participants.

Findings

A total of 26 beliefs were identified: 2 personal goals, 4 advantages, 3 disadvantages, 2 approval-seeking referents, 4 approving normative referents, 2 disapproving normative referents, 4 facilitating factors, and 5 barriers to ethical ChatGPT use (Table 1).

Table 1. Salient beliefs

Constructs	Belief category	Beliefs	N	%
Procurement	Personal goal	Pass course	24	85.7
goal		Save time on assignments	18	64.3
Behavioural	Advantages	Pass course assignments with less effort	26	92.9
beliefs		Improve grades	19	67.9
		Creative ideas for assignments	16	57.1
		Improve understanding of course material	10	35.7
	Disadvantages	Crashed/inoperative	22	78.6
		Risk of plagiarism	18	64.3
		Generic/unhelpful answers	11	39.3
Approval goal	Gain approval	University professors	19	67.9
		Classmates	11	39.3
Normative	Approve	Classmates	23	82.1
		Parents	16	57.1
		University professors	11	39.3
		Employers	9	32.1
	Disapprove	University professors	20	71.4
		Employers	12	42.9
Control beliefs	Easier	Supportive professors/allowing its use	25	89.3
		Clear regulation for use	17	60.7
		Learn prompts/guidance for ethical use	12	42.9
		Relevant/useful assignments	9	32.1
	Difficult	Time constraints	22	78.6
		Unrealistic/challenging assignments	19	67.9
		Excessive assignments	16	57.1
		Ambiguity about ethical vs. unethical use	14	50
		Assignments with a low-grade contribution	11	39.3

Participants primarily pursue ethical ChatGPT use to achieve personal and academic goals. Twenty-four participants (85.7%) identify passing the course as a procurement goal. Eighteen participants (64.3%) use the tool to save time on assignments. Behavioural beliefs regarding advantages centre on efficiency and performance. Twenty-six participants (92.9%) believe it helps them pass assignments with less effort. Nineteen participants (67.9%) expect improved grades. Sixteen participants (57.1%) value the tool for generating creative ideas. Ten participants (35.7%) believe it improves their understanding of course material. Behavioural beliefs regarding disadvantages focus on technical and academic risks. Twenty-two participants (78.6%) identify system crashes as a disadvantage. Eighteen participants (64.3%) cite the risk of plagiarism. Up to eleven participants (39.3%) find the answers to be generic or unhelpful.

Social influence plays a complex role in approval and normative beliefs. Nineteen participants (67.9%) seek approval from university professors. Eleven participants (39.3%) seek approval from classmates. Normative beliefs show a conflict between different social groups. Twenty-three participants (82.1%) believe their classmates approve of the use. Sixteen participants (57.1%) believe their parents approve. Eleven participants (39.3%) perceive approval from university professors. Nine participants (32.1%) perceive approval from employers. Conversely, twenty participants (71.4%) believe university professors disapprove of the use. Twelve participants (42.9%) believe employers disapprove.

Control beliefs indicate various facilitators and barriers to ethical use. Twenty-five participants (89.3%) believe supportive professors make ethical use easier. Seventeen participants (60.7%) identify clear regulations as a facilitating factor. Twelve participants (42.9%) believe that learning prompts and guidance for ethical use makes the process easier. Nine participants (32.1%) find relevant and useful assignments to be a facilitator. Several factors make ethical use difficult for participants. Twenty-two participants (78.6%) cite time constraints as a barrier. Nineteen participants (67.9%) find unrealistic or challenging assignments difficult. Sixteen participants (57.1%) identify excessive assignments as a barrier. Fourteen participants (50%) report difficulty due to ambiguity about ethical versus unethical use. Eleven participants (39.3%) find it difficult to maintain ethical use for assignments with a low-grade contribution.

Discussion

The findings of this study identify specific advantages and concerns regarding ChatGPT use in university settings. These results align with the Strengths, Weaknesses, Opportunities, and Threats (SWOT) analysis proposed by Farrokhnia et al. (2023). Participants recognize several strengths including increased efficiency and improved grades. They also value enhanced creativity and better learning outcomes, which aligns with previous research suggesting that LLMs might have positive impact on creativity (Toma & Yánez-Pérez, 2024). These behavioural beliefs suggest that pre-service teachers view LLMs as a functional asset for their professional development. However, participants also acknowledge significant weaknesses. Concerns remain regarding LLM reliability and the risk of plagiarism. Participants specifically question the quality of generated content and the potential for generic responses.

The data emphasize the critical role of professors in guiding ethical practices. Participants suggest that structured guidance and prompt engineering support from instructors would improve their usage. This finding highlights a gap between the desire for faculty approval and the perceived disapproval from the same group. While students seek to meet academic standards, the lack of clear institutional frameworks creates ambiguity. Providing specific guidance for ethical use would likely bridge this gap and reduce the difficulty associated with navigating new technology.

These results provide empirical evidence for the benefits of ChatGPT discussed by Cooper (2023)

and Dwivedi et al. (2023). The findings also confirm concerns about potential unethical use noted by Kasneci et al. (2023). University students demonstrate an active awareness of these ethical challenges and the technical limitations of LLMs. This study identifies key beliefs that educators can target in future interventions to promote ethical engagement. Specifically, addressing control beliefs such as time constraints and assignment design could reduce the pressure to use AI unethically.

The practical implications of these findings inform the development of strategies to foster an ethical learning culture. Future studies might design and implement interventions that support the integration of LLM tools like ChatGPT. Rather than focusing on misconduct, professional development programs should highlight how LLM can assist in achieving procurement goals ethically. These strategies should include clear regulations and supportive teaching practices to lower the barriers to responsible use. This approach ensures that pre-service teachers develop the necessary skills to use LLM in their future classrooms.

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Generative AI Training For Pre-Service Teachers: Impacts And Adoption Patterns

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This study investigates the impact of targeted training in the use of Generative Artificial Intelligence (GAI) among pre-service Science and Mathematics teachers. Grounded in Rogers' Diffusion of Innovations Theory (DIT), the research examines how structured training experiences influence adoption patterns, pedagogical perceptions, and ethical awareness related to GAI use in educational contexts. The study adopts a quantitative approach and involved 183 pre-service teachers enrolled in initial teacher education programs. Participants took part in practical workshops designed to explore the pedagogical use of GAI tools, particularly ChatGPT, for lesson planning, problem-solving activities, and reflective discussions on ethical implications. Data were collected through pre- and post-workshop questionnaires and analysed using descriptive statistics and cluster analysis. The findings identified six distinct GAI adoption profiles, with Innovative Adopters and Moderate Adopters demonstrating higher levels of pedagogical engagement and greater confidence in integrating GAI into teaching practices. These groups increasingly used GAI to design interactive and personalized educational materials aligned with the goals of science education, such as fostering critical thinking and student engagement. Conversely, more conservative profiles showed resistance to adoption, highlighting the need for differentiated training strategies. Overall, the study underscores the relevance of targeted GAI training in initial teacher education, emphasizing its potential to enhance digital literacy, pedagogical innovation, and ethical awareness among future Science and Mathematics teachers.

Keywords: Generative AI, Teacher Training, Science Education

Introduction

Generative Artificial Intelligence (GAI) is rapidly transforming how teachers plan lessons, create materials, and engage students. Tools like ChatGPT now automate routine tasks, generate personalized content, and support interactive learning—opening new pedagogical possibilities for Science and Mathematics education. Yet this technological promise comes with significant challenges: ethical concerns about bias and misinformation, methodological questions about appropriate use, and pedagogical dilemmas about balancing AI assistance with student learning (García Sánchez, 2023; Sok & Heng, 2024).

The risks of uncritical GAI adoption are well documented. Students may develop technological dependency rather than critical thinking skills, and AI systems can perpetuate biases embedded in their training data (Montesano de Talavera et al., 2023; Avraamidou, 2024). These concerns are particularly acute in Science and Mathematics education, where inquiry, problem-solving, and reasoning form the core of learning. Preparing teachers to integrate GAI reflectively and ethically—rather than merely technically—has therefore become a central challenge for teacher education.

Initial teacher education offers a strategic intervention point. During this formative period, future

teachers develop beliefs, competencies, and dispositions toward technology that will shape their entire professional practice (Koehler & Mishra, 2008; San Andrés et al., 2022). Understanding how pre-service teachers adopt emerging technologies like GAI is therefore essential—not just for individual professional development, but for the broader project of pedagogical innovation in science education.

To examine these adoption processes, this study draws on Rogers' Diffusion of Innovations Theory (DIT), which frames adoption as a non-linear process shaped by individual innovativeness and perceptions of an innovation's relative advantage, complexity, and compatibility (Rogers, 2003). Recent research confirms that more innovative pre-service teachers integrate AI tools in pedagogically richer ways, while less innovative users adopt them cautiously or instrumentally (Uzumcu & Acilmis, 2024). Building on this foundation, the present study investigates how targeted GAI training influences adoption patterns, pedagogical perceptions, and ethical awareness among future Science and Mathematics teachers.

Objectives

The main aim of this study was to analyse the impact of targeted training in the use of GAI among pre-service Science and Mathematics teachers. Grounded in the DIT, the study sought to understand how structured training experiences influenced GAI adoption patterns, pedagogical perceptions, and ethical awareness in initial teacher education.

Specifically, the study aimed to:

1. Identify distinct profiles of GAI use among pre-service teachers, based on adoption patterns informed by the DIT;

2. Examine changes in participants' pedagogical and ethical perceptions of GAI before and after participation in practical workshops;

3. Analyse the relationship between GAI adoption profiles and the evolution of pedagogical and ethical perceptions following the training experience.

Methodology

We conducted a quantitative study to examine how targeted GAI training affects pre-service Science and Mathematics teachers. The sample comprised 183 pre-service teachers (aged 19–21) enrolled in initial teacher education programs.

Between April and May 2024, participants attended practical workshops designed to integrate GAI tools—particularly ChatGPT—into Science and Mathematics teaching. Workshop activities included lesson planning with AI assistance, applying Polya's method for problem-solving, and discussing ethical implications of AI use in education.

We collected data through pre- and post-workshop questionnaires. The pre-workshop instrument assessed participants' baseline GAI use patterns: frequency, diversity of applications, and initial perceptions of pedagogical potential. The post-workshop questionnaire measured changes in pedagogical and ethical perceptions, as well as confidence in using GAI for instruction.

We analysed the data using descriptive statistics and cluster analysis. The cluster analysis, informed by DIT categories, identified distinct GAI adoption profiles among participants. This approach allowed us to examine how adoption patterns relate to changes in pedagogical and ethical perceptions after training.

Results

Two main findings emerged from the analysis. First, pre-service teachers showed heterogeneous patterns of GAI adoption. Second, the training produced statistically significant changes across all perception dimensions ($p < .001$), though the magnitude varied considerably.

GAI Adoption Profiles And Openness To Innovation

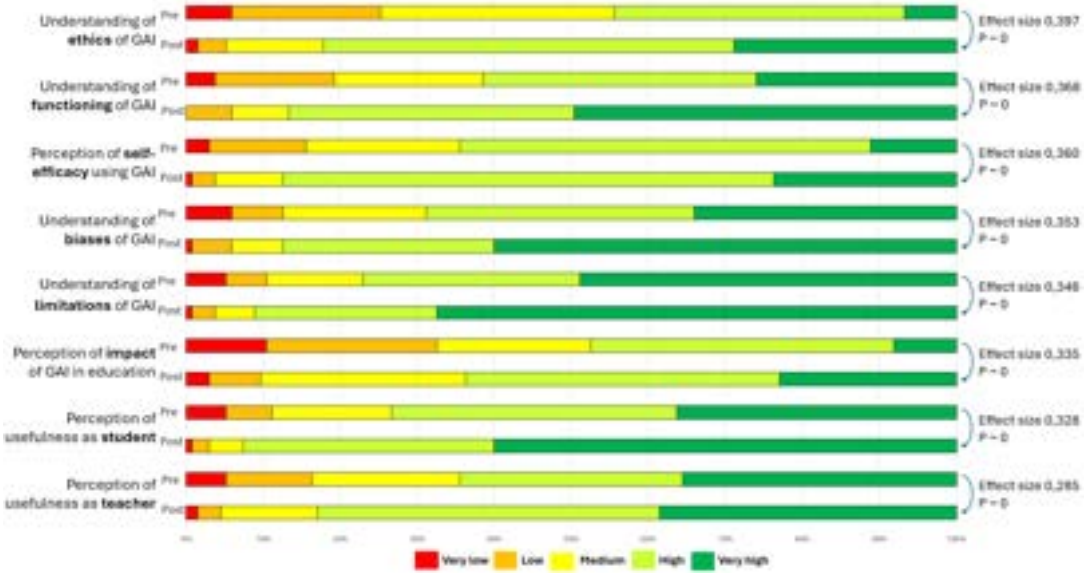
Cluster analysis identified six distinct profiles of GAI adoption: Innovative Adopters (13.97%), Moderate Adopters (33.52%), Conservative Users (22.35%), and three additional profiles (30.16%) showing varying degrees of engagement. These profiles reflect substantial variability in participants' experience, frequency and diversity of use, engagement with extensions and communities, and practices of updating knowledge about GAI tools. When interpreted through the DIT, the profiles can be broadly situated along a continuum ranging from more innovative adopters to more conservative users.

Notably, Innovative Adopters and Moderate Adopters together comprised the majority of the sample (47.49%), suggesting a favourable context for GAI adoption—likely reflecting participants' academic environment and digital familiarity. However, the substantial presence of Conservative Users (22.35%) demonstrates that openness to innovation varies even within digitally oriented cohorts. This heterogeneity validates DIT as an analytical lens for understanding GAI uptake in teacher education.

Differential Effects Of The Training On GAI-Related Perceptions

Wilcoxon signed-rank tests confirmed statistically significant pre-post differences across all perception variables ($p < .001$). As Figure 1 shows, the training consistently improved participants' GAI perceptions, but effect sizes varied substantially across dimensions.

Figure 1. Pre- and post-workshop changes in pre-service teachers' perceptions of Generative Artificial Intelligence.



The largest effect sizes emerged for ethical awareness ($r = 0.397$), understanding of GAI functioning ($r = 0.368$), and self-efficacy ($r = 0.360$). These results indicate that the training most effectively strengthened participants' conceptual clarity about how GAI operates, their confidence in using such tools, and their sensitivity to ethical issues including biases, limitations, and responsible use. In DIT terms, these gains reflect reduced perceived complexity and increased perceived relative advantage—two attributes that facilitate innovation adoption.

Moderate effect sizes characterized perceptions of biases, limitations, and GAI's broader impact on knowledge, learning, and problem-solving. These findings suggest participants moved beyond

purely instrumental views of GAI toward a more critical, reflective stance—increasingly recognizing its epistemic and ethical implications for educational contexts.

In contrast, perceived usefulness for future teaching showed smaller gains (r = 0.285), though still statistically significant. This pattern reveals a critical gap: technical understanding and ethical awareness do not automatically translate into a professional vision of GAI as an integral teaching tool. The distinction between intention and anticipated practice suggests that deeper pedagogical integration may require sustained, practice-based training experiences.

Discussion

This study examined how targeted GAI training affects pre-service teachers' adoption patterns and perceptions, using Rogers' DIT as an analytical framework. The core finding is clear: structured training positively influences how future teachers understand and evaluate GAI. Yet the results also reveal an important boundary—openness to innovation does not automatically translate into pedagogical consolidation.

Through a DIT lens, the strongest changes occurred in ethical awareness (r = 0.397), understanding of GAI functioning (r = 0.368), and self-efficacy (r = 0.360). These gains map directly onto two attributes Rogers (2003) identifies as central to innovation adoption: reduced perceived complexity and increased perceived relative advantage. For GAI—where uncertainty about system functioning and ethical risks often inhibits adoption—such improvements are particularly consequential for fostering informed, responsible engagement.

Moderate effects in awareness of biases, limitations, and GAI's broader impact on knowledge and learning indicate an important conceptual shift. Participants moved from viewing GAI as merely a productivity tool toward recognizing its epistemic and ethical implications—a crucial step in adopting complex educational technologies thoughtfully rather than instrumentally.

In contrast, perceived usefulness of GAI for future teaching practice exhibited comparatively smaller gains (effect size = 0.285), despite remaining statistically significant. This finding highlights a crucial distinction between increased confidence and understanding, on the one hand, and the integration of GAI into teachers' professional identity and anticipated classroom practices, on the other. Consistent with previous research, this result suggests that intentions to use GAI do not necessarily translate into sustained pedagogical practices, particularly when training experiences are short-term or not embedded in authentic teaching contexts.

The identification of heterogeneous adoption profiles further reinforces the relevance of DIT for interpreting these findings. The coexistence of innovative, early adopter, and more conservative profiles within the same cohort suggests that openness to GAI is uneven, even among digitally oriented pre-service teachers. This heterogeneity implies that uniform training approaches may be insufficient to address diverse levels of readiness, motivation, and concern. Differentiated training strategies that consider distinct adoption profiles may therefore be more effective in supporting equitable and sustained integration of GAI in teacher education.

Finally, some limitations of this study should be acknowledged. The reliance on self-reported data captures perceptions and intentions rather than observed teaching practices, and the relatively short duration of the intervention limits inferences about long-term adoption. These limitations are consistent with exploratory studies on emerging technologies and point to the need for longitudinal and practice-based research. Future studies could investigate how repeated and contextually embedded training experiences influence the consolidation of GAI use in classroom practice over time.

Final Considerations

This study demonstrates that targeted training can meaningfully shape how pre-service teachers perceive and approach GAI. The training enhanced ethical awareness, deepened understanding of AI functioning, and strengthened self-efficacy—all prerequisites for thoughtful technology integration. Yet the more modest gains in perceived usefulness for teaching reveal a crucial insight: knowledge and positive attitudes alone do not guarantee pedagogical transformation.

The results suggest that training experiences are particularly effective in addressing dimensions related to ethical awareness, understanding of GAI functioning, and self-efficacy, which are closely associated with reducing perceived complexity and enhancing the relative advantage of the innovation. At the same time, the more modest gains observed in perceived usefulness for future teaching practice highlight that adoption processes are gradual and do not automatically result from increased technical knowledge or positive attitudes alone.

By identifying heterogeneous adoption profiles among pre-service teachers, this study reinforces the relevance of the DIT for understanding how GAI is appropriated in initial teacher education. The coexistence of innovative and more conservative profiles underscores the need for differentiated and sustained training strategies that account for varying levels of readiness, experience, and concern.

This study contributes empirical evidence on how targeted training shapes GAI perceptions and adoption patterns among future teachers. The practical implication is clear: teacher education programs should incorporate structured GAI training that addresses not just technical skills, but ethical awareness and pedagogical integration. Future research should employ longitudinal designs to track how these early experiences translate into sustained classroom practice.

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Design-Based Research To Create A Collaborative Game To Foster Spatial Skills: The Role Of Teachers

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This research explores the role of teachers in the co-design process of a hybrid collaborative game aimed at enhancing spatial skills among students in primary school. Spatial competencies, such as visuospatial perspective-taking and frame-of-reference shifting, are an important part of learning in STEM subjects but often are not explicitly taught. Using a Design-Based Research (DBR) approach, the project integrates immersive virtual environments (VR) with tangible elements to create an equitable and engaging learning experience. Teachers are involved in the design and development phases, providing input that shaped gameplay mechanics to meet curriculum intentions and classroom realities. The game, which combines VR, digital maps, and physical boards, encourages students to solve spatial problems collaboratively while navigating a narrative-driven environment. Preliminary findings reveal how teacher engagement might overcome challenges of equitable engagement, adaptive scaffolding, and integration into the curriculum. The teachers pointed out that the need for visual cues, verbalization of spatial reasoning, and adaptive difficulty levels underlined the support for students with different spatial abilities. Other main orchestration strategies include balancing guidance and student autonomy and transitioning between digital and physical tasks smoothly. These recommendations really point to the importance of collaboration between researchers and teachers in the design of pedagogically relevant and feasible game-based learning environments. This will be further implemented in-class, studying how teachers adapt and scaffold learning within this hybrid environment. This research contributes to understanding how teacher expertise and DBR methodologies can enhance the design and integration of game-based tools for spatial skill development in primary education.)

Keywords: Game-Based Education; Spatial Cognition; Collaborative Learning

Context and Conceptual Network

Spatial Abilities At Stake

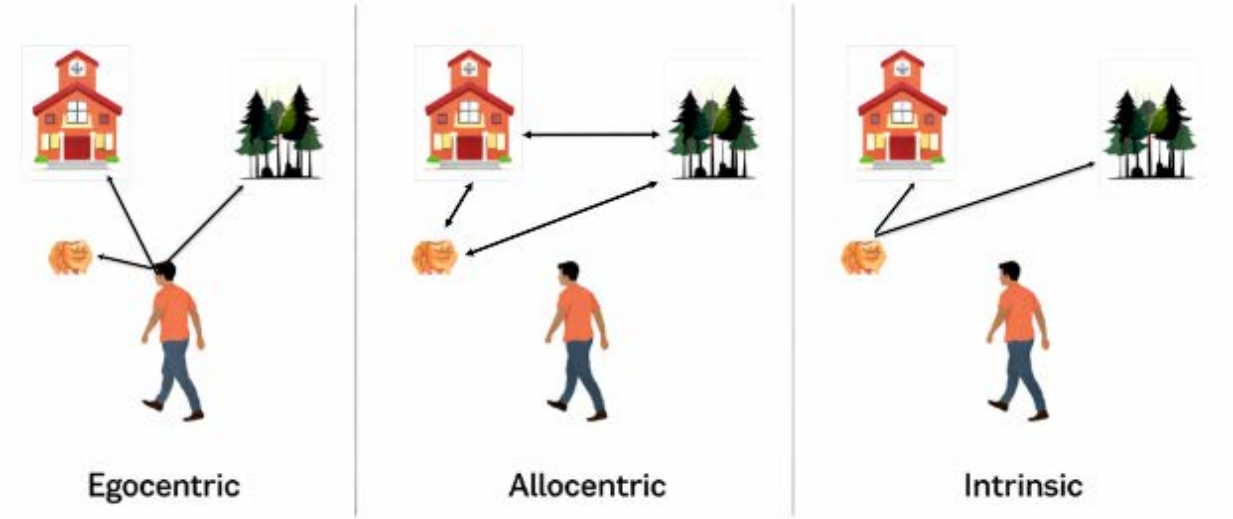
Spatial thinking is significant in science education. It enables students to mentally represent, manipulate, and reason about spatial relationships, which are essential for understanding key scientific concepts and solving problems in disciplines such as mathematics, earth sciences, physics, chemistry and engineering (Newcombe et al., 2023; Tversky, 2005, Uttal, Miller & Newcombe, 2013). Despite its importance, spatial thinking is rarely taught explicitly in primary education (Newcombe et al., 2023). However, research shows that these skills can be trained and effectively transferred to academic tasks (He et al., 2022). Digital technologies, particularly immersive virtual environments (VE), provide promising opportunities to support this development, especially for students with lower spatial abilities (Makransky & Petersen, 2023).

The present contribution is part of a four-year project aimed at designing and evaluating collaborative game-based learning environments to enhance spatial thinking in primary school students.

Two key spatial competencies are at the core of the project: visuospatial perspective-taking and frame-of-reference. Visuospatial perspective-taking is designed as “the ability to infer the visual or spatial properties of a scene in relation to another person or position” (Samuel et al., 2024).

Frame of Reference Shifting is the ability to switch between different spatial reference frames to process and interpret spatial information. There are three main types (Figure 1.). The egocentric frame is defined relative to one's own position (e.g., the dog is on my left). The allocentric frame is based on external landmarks and fixed coordinates (e.g., the dog is south of the school). Finally, the intrinsic frame is determined by the objects themselves (e.g., the school entrance is in front of the dog's tail).

Figure 1. Three Frames of Reference.



Hybrid Environment: Equity And Teacher's Orchestration

By integrating game-based interactions with immersive virtual environments, the project aims to foster spatial competencies by ensuring an equitable learning experience for every student. Indeed, there exist differences regarding gender, socioeconomic background, and prior exposure (Newcombe et al., 2023). The lack of consideration for inclusion in the design process of digital environments may aggravate these gaps (Gottschalk & Weise, 2023). In our project, we will adopt a hybrid approach that combines virtual reality and tangible elements to maximize inclusion by fostering the engagement of all students. More specifically, the learning environment will integrate virtual interactions with board-style physical elements. In this context, the challenge for teachers will be to effectively orchestrate the gaming sessions to ensure that all students can develop spatial skills in an equivalent manner.

In game-based learning, teachers must integrate games that align with academic objectives and learning goals (Arnab et al., 2012). Moreover, real-time feedback is crucial for tracking progress and enabling timely intervention, helping to maintain student engagement (Holstein et al., 2019). However, implementing these games effectively requires balancing student autonomy with structured guidance, which calls for dynamic orchestration strategies (Dillenbourg & Jermann, 2010). Ultimately, the success of game-based learning depends on teachers' involvement in both the design process and classroom integration (Sanchez, 2022). Therefore, teacher's involvement during the design process is an interesting avenue.

Teachers' Role In Co-Design Of The Game

The project uses a Design-Based Research (DBR) approach to design, develop and implement the collaborative game-based learning environment (Sandoval & Bell, 2004). DBR is a participatory, iterative methodology that involves two interconnected cycles of design, implementation, analysis, and refinement. This approach actively involves teachers at every stage, ensuring that their needs and perspectives shape the game design. As a result, the game is both research-informed and practice-oriented, increasing its relevance and likelihood of

integration into classroom practices (Sanchez & Monod-Ansaldi, 2015).

In particular, teachers are actively involved in two key moments: (a) the design and development phases, and (b) the implementation and evaluation phases. During the design and development phases, teachers collaborate with researchers and developers to create the game. In the implementation and evaluation phases, their role shifts to orchestrating students' actions and social interactions within the game environment.

This study examines the role of teachers in the design and development phases of the game. Specifically, it focuses on three key dimensions: how teachers draw on their teaching experience to inform the design process, how they anticipate orchestrating the game in the classroom, and how this projected orchestration influences the design and development of the game prototype. The aim is to understand how teachers' active involvement in these phases contributes to creating a game that is both pedagogically relevant and aligned with classroom realities.

In this context, we analyse the role of teachers in two aspects:

- Teachers as Co-Designers: game design sessions were conducted, bringing together four researchers, one developer, three primary school teachers, and one external expert. It shaped a narrative-driven collaborative game where students explore, manipulate, and co-construct spatial representations through multimodal interactions (VR headset, physical board, digital maps). The game mechanics were developed to support spatial frame of reference shifts and visuospatial perspective-taking, fostering equitable collaboration and knowledge-sharing among students (Olsen et al., 2021).
- Expected Teacher Orchestration in the Classroom: Teachers must strike a balance between student autonomy, scaffolding, and instructional direction to ensure equitable involvement (Koehler & Mishra, 2009). Focus is placed on teacher orchestration techniques, such as managing the shift between digital and physical activities, providing real-time student support, and implementing adaptive interventions.

Preliminary Insights

During first sessions, the first version of the game prototype was co-designed for the stimulation of collaboration, spatial exploration, and problem-solving. It integrated physical board, digital tablet, and VR headset.

Players take on the role of explorers in this intricately created universe, tasked with reestablishing harmony in the cursed middle-age city of Luméria. Through cooperative navigation and spatial problems in an interesting, dynamic environment, students acquire important spatial competencies.

Integrating Spatial Skills Into Game Mechanics

During the game design sessions, the teachers and the researchers embedded spatial reasoning tasks into the game, jointly ensuring that it will support perspective taking, frame of reference shifts, and cognitive mapping.

A key objective is to help students adopt multiple viewpoints in a 3D environment. To do so, the game follows a progressive difficulty structure, starting with egocentric tasks (e.g., "describe what you see") before moving to allocentric tasks (e.g., "navigate using a landmark"). Teachers agreed on the value of visual clues such as maps, icons, and directional indicators to support frame transitions and to orient the students and facilitate the interpretation of spatial information

across perspectives.

The hybrid game model of VR, physical board, and digital maps supports students in creating and updating their cognitive maps. Teachers emphasized the importance of students verbalizing their spatial reasoning; therefore, collaborative reflection questions were added to have them explain their navigation choices and strategies to their peers.

Equity In Spatial Skill Development

A preoccupation of the research is that pupils with poorer spatial skills might find it difficult to participate in activities that require intricate perspective changes. Teachers underlined how having to switch between frames of reference could cause these pupils to become disinterested or frustrated.

To handle this, the game design is planned to incorporate adaptive scaffolding mechanisms. To ensure that they gain spatial competencies at their own rate, students are given customized and guided navigation prompts.

Alignment With Curriculum & Classroom Feasibility

Making sure the game fits with STEM learning objectives without adding to teachers' workload in terms of class preparation and planning was another important consideration. Teachers emphasized that rather than requiring separate instructional time, spatial learning should be smoothly integrated into current curricula. By integrating spatial tasks into subjects like geography (map reading, landmark), mathematics (spatial transformations, coordinate systems), French (vocabulary, verbalization), biology, and physics (motion, reference frames), the game design aims to address this problem by fostering cross-disciplinary connections.

Challenges & Affordances In Classroom Implementation

Teachers projected several pedagogical constraints and agreed with researchers on opportunities in integrating game-based spatial learning into primary education (Tab. 1).

Table 1. Opportunities and Challenges in Orchestration.

	Affordances (Opportunities)	**Challenges (Constraints)**
Time Managment	Encourages active, multimodal engagement, helping students bridge virtual and real-world spatial reasoning.	Managing time constraints while integrating the game into existing STEM lessons.
Equitable Collaboration	Collaborative problem-solving fosters spatial reasoning.	Ensuring that low spatial ability students do not disengage.
Guidance	Teachers can use scaffolding strategies (e.g. hints) to gradually fade support.	Feedback: Balancing teacher guidance vs. student autonomy in open-ended navigation tasks.
Diversity of Media	Using hybrid tools (VR, digital maps, artifacts) ensures multiple entry points for learning.	Classroom logistics for handling VR equipment and transitions between digital/physical tasks.
Game Universe	Keep in mind the necessity of a narrative and game universe that are age-appropriate and engaging for primary school students.	

Preliminary co-design results reveal interesting tensions in integrating game-based virtual environments. Teachers highlight challenges in time management, participatory equity, and orchestration load, while their perceptions of students' spatial skills and engagement shape

curriculum integration. The next phase will examine classroom implementation, focusing on how teachers adapt, scaffold, and co-regulate learning in this hybrid environment.

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Designing Digital STEM Teaching-Learning Sequences By Primary Pre-Service Teachers

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Digital technologies offer opportunities to enhance teaching by providing interactive and immersive learning experiences. The research on the connection between digital learning objects in learning management systems to implement teaching learning sequences (TLSs) is rather limited. To this end, Digital Learning Objects (DLOs) and Learning Activity Management Systems (LAMS) are useful digital tools. DLOs are defined as digital resources which correspond to learning activity types. Learning activity types are distinguished in three categories: a) Knowledge-building, b) Convergent Knowledge Expression and c) Divergent Knowledge Expression. In addition, using LAMS tools TLSs could be structured. Therefore, LAMS platforms and DLOs can play a central role in developing TLSs in STEM education. In the present paper we will present a study investigating the way primary pre-service teachers design digital STEM TLSs using the LAMS platform. In the study participated 17 pre-service teachers in third and fourth year of their bachelor's degree in primary education. The participants were randomly divided into six subgroups (five groups of three and one group of two) and developed digital TLSs focused on the topic of Climate Change. For the analysis qualitative methods of content analysis were used based on the digital TLS developed by pre-service teachers in the LAMS platform. Our results provide evidence of the connection between the types of learning activities and the possibilities offered by the digital tools and indicate that using Digital Learning Objects enhance the Digital Learning Sequences in STEM education and pre-service teachers are capable of designing coherent, linear digital STEM sequences that prioritize content exploration and guided inquiry.

Keywords: Digital Learning, Digital Resources, e-Learning

Introduction

Digital technologies offer unique opportunities to enhance teaching by providing interactive, inquiry-based, and immersive learning experiences (Hsu, 2012). The use of digital technologies in education, especially after the COVID-19 pandemic, has increased considerably. Since teachers are responsible for designing and structuring lessons, it is crucial to effectively integrate Technology into them. The TPACK framework (Mishra & Koehler, 2006) supports the effective integration of technology into teaching. Effective lesson planning is essential in science education, as it significantly enhances teaching quality and improves student outcomes (Groβmann et al., 2024). A key approach integrating digital tools in education involves the development and use of Digital Learning Objects (DLOs)—digital resources that facilitate specific learning objectives and promote student engagement (Kay & Knaack, 2008). Based on the above, developing Teaching-Learning Sequences (TLSs) (Psillos & Kariotoglou, 2016), provide coherent and inquiry-driven frameworks for addressing complex STEM topics like climate change.

Learning Management Systems (LMS) are platforms that provide a range of digital tools, like chat, forum, document repository etc within a course. One of the many options of LMS platforms is the Learning Activity Management System (LAMS) platform. While LAMS provides tools similar to standard LMS platforms, it uniquely facilitates the structuring of digital TLSs by sequencing learning activities. DLOs can be part of the content of the various platform's tools.

Since LAMS platform support DLOs positively (Levy et al., 2009), pre-service teachers (PSTs), acting as TLS designers, can play a central role in STEM education. A group of LAMS tools form learning blocks. The learning blocks correspond to learning activity types. Group of blocks may form larger learning blocks, supporting learning activities in an inquiry-based framework. According to the categorization of Harris et al. (2009), learning activity types may belong to the following categories:

a) Knowledge-building (e.g., Read text),

b) Convergent Knowledge Expression (e.g., answer questions), and

c) Divergent Knowledge Expression (e.g., do a presentation).

In our study, the development of TLSs was structured in the LAMS platform. The platform provided tools categorized as:

a) Flow (Gate, Grouping etc.),

b) Evaluation tools (Assessment, like Multiple Choice and Reflective, like Question & Answer),

c) Collaboration (Chat, Forum etc.), and

d) Content (Noticeboard etc.).

LAMS tools can be used to organize TLSs according to the flow of the designed sequence. For example, the gate tool can be used when the designer wants participants to reach a specific point in the TLS before all the participants move forward. In the same line, the grouping tool can be used in order to create groups dealing with different activities.

This study examines the following research question: How do primary pre-service teachers design digital STEM Teaching-Learning Sequences? In particular we investigate the learning activity type integrated by pre-service teachers in the design of a digital TLS about climate change in the LAMS environment.

Research Context And Implementation

The research was conducted under the European Union Erasmus+ project STEM-DIGITALIS. The aim of the project was to develop digital tools and learning objects for advanced STEM topics, like climate change, renewable energy (RE) sources, etc. Within this framework, four (4) Digital Learning Objects (DLO) were developed to facilitate inquiry-based learning and provide immersive, interactive experiences for students. The four DLOs included two interactive graph representations, an interactive video, a computer game, and an augmented reality (AR) application. These TLSs were structured according to the Model of Educational Reconstruction (Duit et al., 2012), which emphasizes the integration of scientific content, student perspectives, and effective teaching strategies. Below it is a short description of the three units:

The first TLS focuses on the correlation mechanism between global temperature and CO_2 concentration. It is based on a serious game, designed with Unity 3D platform, where participants navigate through the last four decades, searching for evidence on the correlation between CO_2 concentration and temperature. The game is assisted with hotspots and players access additional information, such as interactive graph representations, an interactive video, answer multiple-choice questions and explore online dashboards for visualizing trends and drawing conclusions. The game is designed to foster critical thinking and data analysis skills, enabling participants to explore the correlation between rising global temperature and increasing CO_2 concentration.

The second TLS shifts focus to the anthropogenic activities that contribute to climate change and

the mitigation measures individuals can take. This TLS utilizes interactive maps and a mobile application to engage participants. The maps display data on CO_2 emissions per country and per activity (e.g., transportation, energy use), providing a global perspective on CO_2 emissions. The application allows the users to calculate their personal CO_2 footprint based on their daily activities. Users have choices on two daily personal activities: transportation and electrical device use. The results are visualized through daily pie charts, offering an understanding of their personal environmental impact, encouraging reflection on mitigation strategies.

The third TLS explores the socio-scientific dimensions of RE, particularly the challenges and opportunities associated with transitioning to climate neutrality. This TLS employs an augmented reality (AR) application and a "treasure hunt" activity to engage participants in role-playing and collaborative problem-solving. Participants are divided into groups and assigned roles (e.g., politicians, activists, researchers, etc.) to represent different stakeholder views in the debate. Using the AR application, participants scan images to access information, solve riddles, and examine the perspectives of stakeholders. This activity enhances critical thinking, negotiation skills, and the understanding of the complex social implications of RE policies.

The TLSs were introduced in a seminar entitled "Digital Tools in Science Education", offered to 17 PSTs, in third and fourth year of their bachelors in primary education. The participants had attended one compulsory foundational course on the concepts of physics and one on the principles of science education. The participants were randomly divided into six subgroups (five groups of three and one group of two) to encourage collaboration and peer learning.

The seminar was structured into three phases:

- Introductory Phase: It introduced participants to various digital tools used in STEM education, including interactive videos, graphs, infographics, games, mobile applications, AR, and digital labs. The participants focused on the attributes, benefits and drawbacks of each tool. The LAMS platform was presented, highlighting its features for designing and managing TLSs.
- Familiarization Phase: Participants engaged with the three pre-designed TLSs on climate change (CC), utilizing different DLOs. They experienced TLSs as learners and reflected on their potential application in future teaching practices.
- Design Phase: Participants designed their own digital TLSs using the introduced DLOs, enriching them with other activities and tools. Each PST group developed a unique TLS on a CC-related topic, applying the knowledge and skills acquired during the seminar.

Data Collection & Analysis

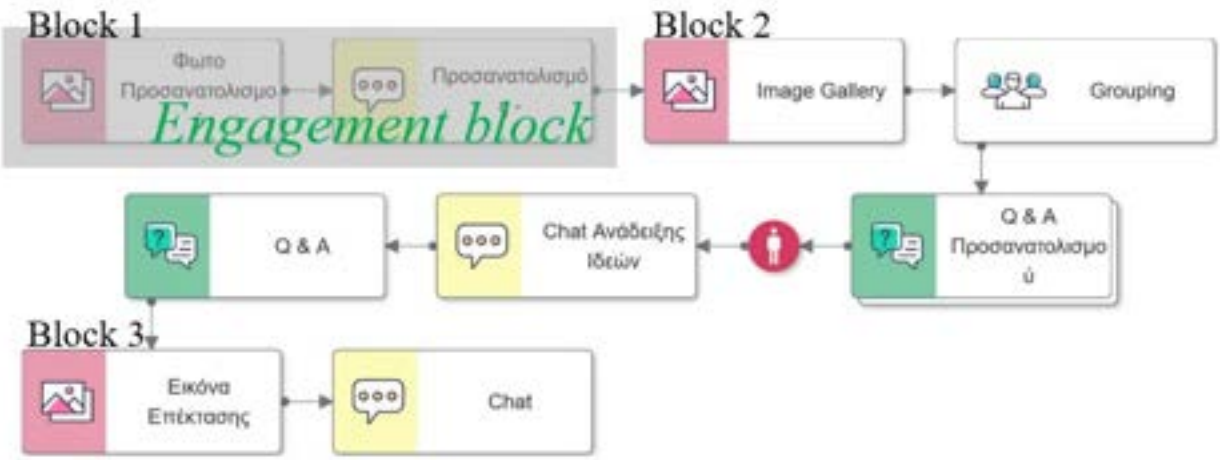
The analysis focused on how the PSTs integrated the DLOs and other types of learning activities within each digital TLS.

The topics of the PST-designed TLSs included:

1. Climate Change and Electric Tranportation,
2. Human Factors Affecting Climate Change,
3. Transportation and Climate Change,
4. The CO_2 footprint of Food,
5. Human Activities and Sustainable Development, and
6. The Personal CO_2 Transportation Footprint.

A variety of technologies were used to support the digital TLSs. Scaffolding activities created larger blocks guiding students through the inquiry process in developing TPACK and Technology-assisted, inquiry-based TLSs. A sample TLS is shown on Image 1. The first two blocks formed the engagement activities of the TLS (Image 1 – Engagement Block).

Image 1 Sample TLS (Group1 - Climate change and electric transportation).



To analyse the data, we used qualitative method of content analysis (Mayring, 2015). As Harris et al. (2009) suggest, the possible categories of learning activity types follow the schema shown in Table 1:

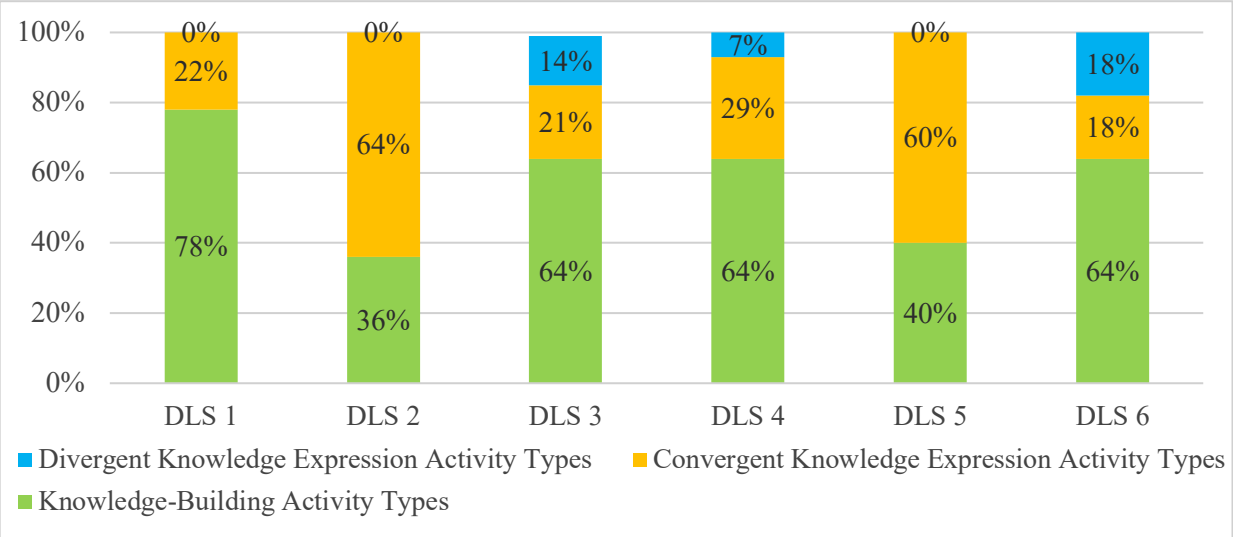
Table 1 Data Analysis Categories

CATEGORIES	CRITERIA	Example
Knowledge-building	Provide information and promote the understanding for the students for the necessary content-related information-building	Read text, view presentation, view images, etc.
Convergent Knowledge Expression	Handle types of tools that "structure representations of prior knowledge building".	Answer questions, take a test, etc.
Divergent Knowledge Expression	"Extend the students" content-related understanding by communicating the content to a wider audience.	Create an illustrated map, do a presentation, etc.

Results

There is diversity on the learning activity type categories. Every sequence used different LAMS tools/activities. The total number of the LAMS tools used in the six TLSs is seventy-four (74). The percentage distribution of the three learning activity type categories across the six digital learning sequences, based on the schema presented above, is shown in Figure 1. Summative results indicate that all the TLSs used activity-type tools for Knowledge-building and Convergent Knowledge Expression. Knowledge-Building activity types prevail among the three categories examined and the Convergent activity types come second out of all. The three of six sequences integrate all three learning activity type categories. Four sequences use Knowledge-building activities in a rather high rate in contrast to the other two learning activity type categories.

Figure 1 Distribution of the four activity types in TLSs



As we delve deeper into each of the three categories, the distribution of learning activity types used with respect to Knowledge-building category is shown in Figure 2 A total of thirty-eight (38) LAMS tools were identified within this category. Debate and Simulation activities featured prominently. In contrast, the Complete Charts/Tables, Research and Devise a story activities barely register.

Figure 2 Knowledge-building activity types of the six DLSs.

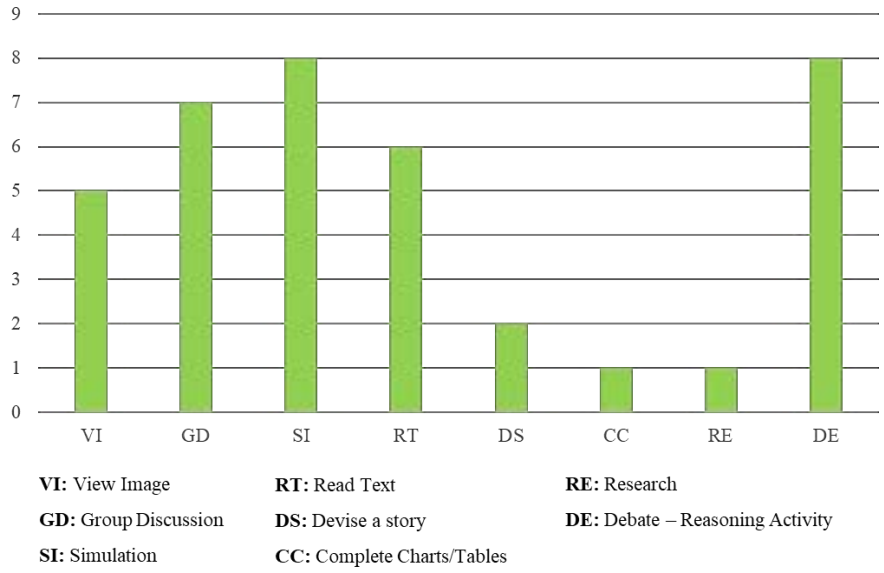
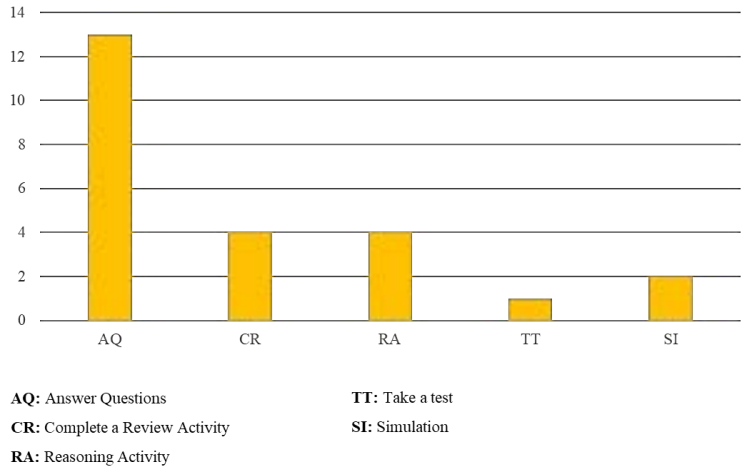


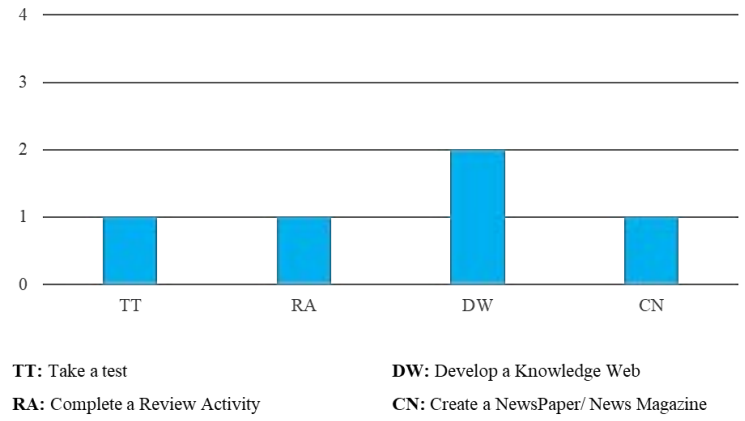
Figure 3 shows the distribution of Convergent Knowledge-building activity types among the six TLSs. This category comprises twenty-four (24) LAMS tools. The distribution reveals a pronounced dominance of the Answer Questions category. The remaining categories constitute the remaining proportion of the total.

Figure 3 Convergent Knowledge building activity types of the six DLSs.



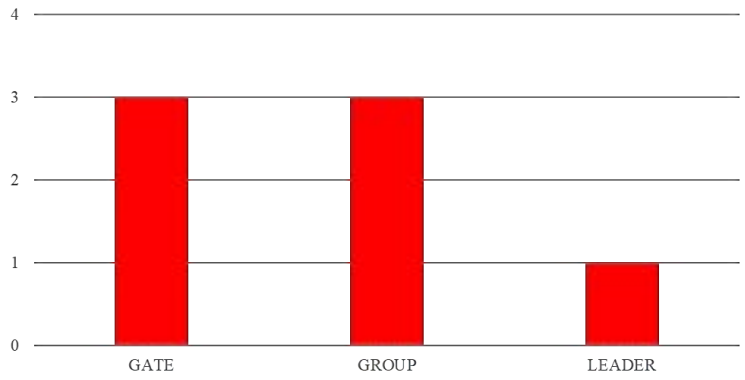
As shown in Figure 4, the Divergent Knowledge-building representation is the least populated category. Specifically, only five (5) LAMS tools were identified across three out of the six TLSs.

Figure 4 Divergent Knowledge building activity types of the six DLSs.



The flow tools category composes an important role at the sequences. Although the flow tools have rather technical attributes, than pedagogical or content specific attributes, they can contribute on a well-structured and well-designed digital sequence. These tools can split students into groups, create different learning paths for the students and other kind of structural options. In our findings, seven (7) LAMS flow tools used in three of six sequences.

Figure 5 Flow tools used into the six DLSs.



Conclusion/Discussion

Our research examined how primary pre-service teachers (PSTs) design digital STEM Teaching-

Learning Sequences (TLSs) within the LAMS platform, with a specific focus on the learning activity types they integrate into their digital sequences. The analysis of the six PST-designed TLSs reveals the design priorities of digital sequences.

The data confirms a preference for Knowledge-building and Convergent Knowledge Expression learning activity types, within the LAMS environment. The high frequency of structured activities like debates, simulations, and answering questions indicates that PSTs effectively leverage digital tools to deliver content and scaffold understanding through structured, guided inquiry. These findings highlight the PSTs' preference in choosing digital tools that correspond with specific objectives regarding content exploration and formative evaluation.

While PSTs' digital designs show familiarity in activities belonging in Knowledge-building and Convergent Knowledge Expression learning activity types, there is a notable lack of use Divergent Knowledge Expression activity types. The tools intended for use as activities in Divergent Knowledge Expression category suggest a more inspired and open-inquiry driven lesson structure. Therefore, the PSTs' digital designs show a tendency toward the design of clearly guided inquiry driven digital sequences.

Moreover, the limited use of flow tools (like gate, grouping and branching) indicates a strong preference among PSTs for linear digital learning sequences. In addition, Digital Learning Objects were only used in Knowledge-building and Convergent Knowledge Expression learning activity types. The use of DLOs was limited to those characterized by simplicity with direct functional value, like a mobile application for calculating personal carbon dioxide footprint. As a conclusion, a deeper understanding of digital tools' attributes and properties equips PSTs with the familiarity needed to utilize them more skilfully and flexibly.

A limitation of our research is its focus on the design phase by the PSTs. The effectiveness of the sequences in actual settings, in-class or remotely, is to be evaluated. Future research should therefore implement these sequences in real teaching contexts to assess their impact on student learning outcomes and engagement.

In summary, our results indicate that using Digital Learning Objects enhance the Digital Learning Sequences in STEM education and pre-service teachers are capable of designing coherent, digital STEM sequences that prioritize content exploration and guided inquiry.

Acknowledgement

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Digital Experimental Protocols And Literacy: Interventions For More Learner Support In Science Education

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Adapting experimental protocols from professional scientific formats is a traditional but challenging writing task in science education. These formats often provide limited guidance and involve specific difficulties such as disjointed sections, impersonal language, and unclear expectations regarding the audience. Language barriers further complicate matters for second language learners and native speakers with developing literacy skills, making protocols a daunting prospect for students. Despite these challenges, however, experimental protocols provide valuable opportunities for students to develop systematic documentation and data analysis skills, thereby enhancing their understanding of science. To facilitate the writing process, a student-centred approach has been proposed that uses redesigned protocols to divide the text into boxes containing sentences, connected by arrows across the results and discussion sections. Targeted writing scaffolds also support sentence construction.
This pilot study investigates whether a fragmented digital protocol format and the use of procedural language support increase students' perceived cognitive load compared to more traditional formats. A 2×2 design was implemented in four-year 8 physics classes (n = 78) during a four-lesson unit on motion and inertia, with two documentation formats (traditional vs. fragmented) and two types of language support (classical vs. procedural). Cognitive load was measured after the intervention using a nine-item questionnaire. The results show no significant differences in perceived cognitive load between the different documentation formats and types of language support. Therefore, despite their structural novelty, neither the fragmented protocol structure nor the procedural writing scaffolds led to increased cognitive load. These findings suggest that structural and linguistic design modifications can be introduced without overloading students cognitively. Ongoing analyses will examine how these design features influence the quality and structure of students' experimental documentation.
Keywords: cognitive load, laboratory reports, scaffolding

Theoretical background

Writing Experimental Protocols As A Linguistic And Cognitive Challenge

Experimental protocols are a traditional, yet challenging, writing task in science education. In particular, the linear text format—into which different types of statements (e.g., observations/results, and interpretations) must be integrated—requires a high level of linguistic competence (Bayrak et al., 2015; Boubakri et al., 2015). In conventional lab reports, clearly separated sections (e.g., observation vs. interpretation) support structure, but the purely linear production of text often makes it difficult to construct explicit argumentative links between results and their interpretation. This linkage, however, is central to scientific knowledge generation (Köhler & Meisert, 2025). For learners of German as a second language, as well as for first-language learners with weaker academic language proficiency, it is particularly challenging to navigate complex subject content and demanding linguistic structures simultaneously (Leisen, 2010; Childs et al., 2015) and even proficient speakers face difficulties due cognitive and structural complexity (Müllner et al., 2024; Heinicke & Friedrich, 2023).

To meet these demands, support measures are needed that combine disciplinary language, visual, and structural elements (Groß & Reiners, 2012; Leisen, 2010, 2022; Schmölzer-Eibinger et al., 2018). Digital writing environments offer additional potential in this respect, as they reduce the constraints of strictly linear text production and allow for flexible revision, rearrangement, and

linking of text elements (Clark & Mayer, 2016; Heinicke & Friedrich, 2023).

Structural Scaffolding Through Text Fragmentation And Visual Linking

One promising approach is the fragmentation of experimental protocols into smaller, functionally defined text units that can be visually linked to each other using arrows or other symbolic connectors, for example. Rather than listing observations first and interpreting them in a separate section later, this design enables students to link results and interpretations directly and step by step (see figure 1).

Figure 1. Traditional linear protocol format (left) vs. fragmented protocol format (right).



The fragmented protocol design makes it possible to link results and interpretations directly and to visualize their relations by means of arrows. In contrast to the classical linear protocol—in which observations and interpretations are strictly separated into their own sections—relationships can thus be reconstructed in smaller steps and with greater transparency (Groß & Reiners, 2012). The increased density of logical and linguistic connections between observations, data, and interpretation also facilitates the construction of argumentative or descriptive relations (Stein & Stumpf, 2019), improves clarity, and creates flexible options for additions and corrections during the writing process (Clark & Mayer, 2016; Heinicke & Friedrich, 2023). The decomposition into individual components additionally directs attention to subaspects and linguistic markers such as procedural expressions (Feilke & Rezat, 2020). Control questions, action prompts, and procedural language patterns make the requirements of individual protocol segments explicit and support the planning of the writing process (Feilke & Rezat, 2020; Krabbe, 2023).

Linguistic Scaffolding: From Classical To Procedural Language Aids

Students need more than just structural scaffolding; they also need linguistic support to cope with the genre-specific requirements of experimental protocols. In science education, so-called classical language aids are widely used for this purpose. These include word fields, sentence starters, writing frames and partially pre-formulated text elements (Leisen, 2010). Their primary function is to facilitate text production and reduce linguistic barriers at the formulation stage. Unlike these approaches, procedural language aids are based on the concept of text procedures (Feilke & Rezat, 2020). As well as supporting formulation, they explicitly address the function and epistemic purpose of each text segment. This is typically achieved through structured prompts, control questions and procedure-specific linguistic patterns that guide students through the processes of planning, monitoring and justifying their writing.

Figure 2. Classical language aids according to Leisen (2010) – word fields. (left) vs. procedural language aids (Krabbe, 2023; Feilke & Rezat 2020; Feilke & Rezat, 2021; Krabbe, 2023) – structered prompts (left), control questions (right).

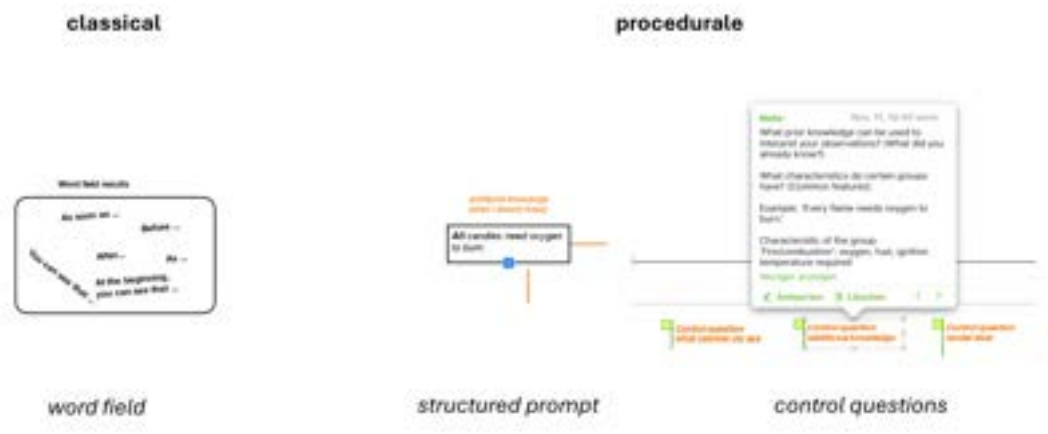


Figure 2 illustrates the conceptual difference between classical language aids, such as word fields and sentence starters, and procedural language aids, which are based on structured prompts and guiding questions (Krabbe, 2015, 2023; Feilke & Rezat, 2020). While the former primarily provide guidance on phrasing, the latter focus on the type of epistemic action to be performed in a given text segment (e.g. describing, justifying or interpreting). Procedural language aids therefore not only aim to reduce linguistic load, but also to foster a more explicit understanding of the writing task itself and the functional architecture of experimental protocols. In this sense, they can be understood as scaffolds that address the linguistic and epistemic dimensions of scientific writing.

The Tension Between Scaffolding And Cognitive Load

Although both fragmented protocol structures and procedural language aids offer significant support for students' scientific writing, they introduce new representational formats and increased orientation requirements. According to cognitive load theory, such design changes may initially increase extraneous or intrinsic cognitive load, particularly when learners encounter unfamiliar structures or multiple representational systems (Krieglstein et al., 2023). This creates a fundamental design tension: On the one hand, scaffolds should make relations, functions, and expectations more explicit, thereby reducing unnecessary cognitive demands. However, every additional structure, symbol system or prompt also constitutes an element that must be processed, understood and coordinated.

Therefore, the central design challenge is not to maximise scaffolding, but to calibrate support so that it reorganises and redistributes cognitive demands rather than simply adding new ones. Whether fragmented protocol structures and procedural language aids achieve this balance is therefore an empirical question rather than a purely theoretical one.

Research Questions

Against this background, the present study addresses the following research questions:

RQ1: Does a text-fragmented and visually structured experimental protocol lead to higher perceived cognitive load than a traditional linear protocol format?

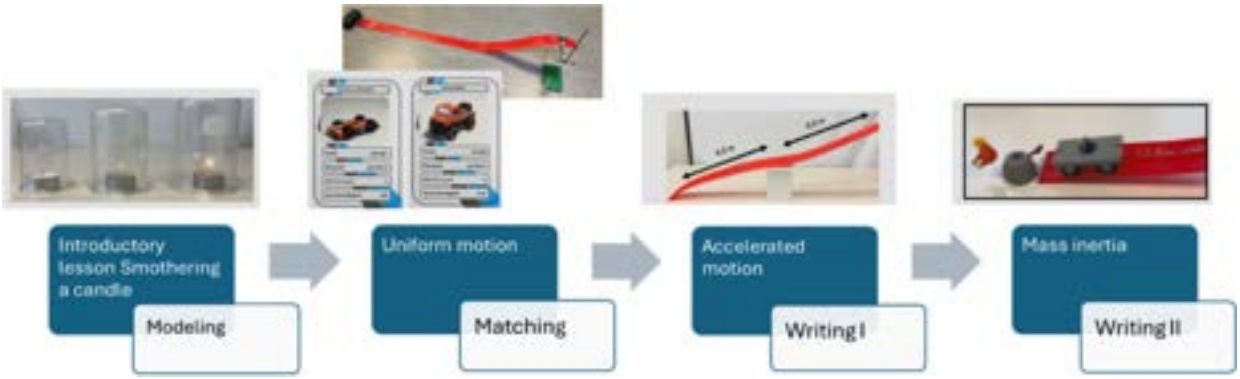
RQ2: Do procedural, function-oriented language aids lead to higher perceived cognitive load than classical formulation-oriented language aids?

Research method and design

This study used a 2×2 design comparing two documentation formats (traditional vs. fragmented) and two types of language scaffolding (classical vs. procedural). The design resulted in four experimental conditions with post-measuring of perceived cognitive load as dependent variable.

A four-lesson physics unit on motion and inertia was completed by four seventh-grade classes (n=78). Depending on their assigned condition, students progressed from guided modelling (Lesson 1) over scaffolded practice (Lesson 2) to unsupported use (Lessons 3–4).

Figure 3. 4-lesson sequence on motion and inertia, showing the materials (above) and the language aids with decreasing level of instruction and support (below) used during the lessons.



Cognitive load was measured using a 9-item Likert scale (1–5), which was adapted from Krieglstein et al. (2023). These items addressed students' perceived mental effort, structural clarity and ease of orientation when working with the digital experimental protocol (e.g. 'The explanations of the protocol sections were difficult to understand'). The questionnaire was administered as a post-test after the fourth lesson and referred to students' experiences with the documentation format and language aids used during the unit.

As the data violated normality assumptions and sample sizes were limited, non-parametric statistical procedures were employed for the primary analyses. Group differences in cognitive load were examined using Mann–Whitney U tests. Additionally, Welch's t-tests were employed as robust parametric comparisons tolerant of unequal variances and group sizes. Effect sizes are reported as r for non-parametric tests and as η^2 for Welch tests (Bortz, 2005).

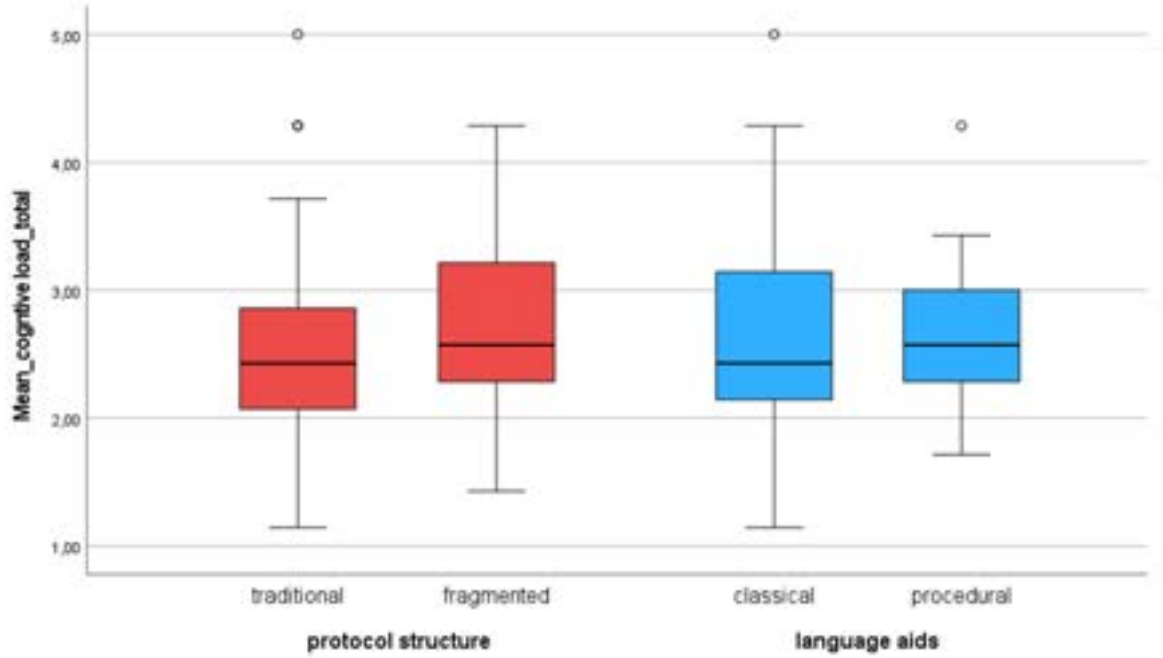
Results

The used cognitive load scale demonstrates good internal consistency (Cronbach's $\alpha = 0.816$).

Valid cognitive load data is available for group comparisons from n = 78 students (traditional format: n = 43; fragmented format: n = 35). Descriptively, mean cognitive load values are very similar across conditions. Students using the traditional format achieve a mean score of 2.53 (SD = 0.77; median = 2.33), whereas those using the fragmented format achieve a mean score of 2.56 (SD = 0.62; median = 2.56) (see figure 4, next page).

No statistically significant difference in cognitive load is found between the two protocol formats (Mann–Whitney $U = 672.50$, $Z = -0.805$, $p = .421$, $r \approx .09$). The corresponding Welch test also shows no significant effect (Welch's $F(1, 75.99) = 0.032$, $p = .858$, $\eta^2 < .01$). Tests of variance homogeneity is non-significant (all $p > .40$).

Figure 4. Paired box plot of the cognitive load of the protocol structure (left) and language aids (right).



Discussion

The present results show that the fragmented protocol format does not lead to a higher perceived cognitive load than traditional, linear documentation. This is a notable finding, given that the fragmented format introduces an unfamiliar structure to the documentation process and could therefore be expected to increase the demands of orientation and navigation (Krieglstein et al., 2023).

Two factors may help to explain this result. Firstly, the introduction of the fragmented format followed a gradual fading strategy with guided examples, which likely reduced the effects of initial disorientation. Secondly, the functional design of the format itself may compensate for its novelty. While the fragmented format introduces a new representational structure, it simultaneously reduces demands relating to strictly linear text production, linguistic planning and integrating different types of statements into a single, continuous text (Clark & Mayer, 2016; Heinicke & Friedrich, 2023). These reductions may offset the additional demands of navigating a segmented representation, resulting in overall cognitive load levels comparable to those of traditional formats. A central design intention of the fragmented format is to strengthen the argumentative link between observations, data, and interpretations. This addresses a well-known weakness of experimental protocols (Groß & Reiners, 2012) (Ref.?), whereby interpretative statements are often only weakly connected to the underlying observations and results. The visual structuring and explicit linking of these elements is intended to help students construct more coherent evidential relations. Ongoing qualitative analyses of the protocols will examine whether this functional promise is actually realised in students' documentation.

A similar pattern emerges when procedural writing scaffolds are used. While conventional language aids enable students to produce text quickly with minimal reflection, procedural scaffolds require them to engage more explicitly with the function and structure of each protocol section and its specific requirements. In principle, this could increase cognitive load. However, the absence of such an increase suggests that greater task transparency and clearer orientation

may stabilise or even reduce perceived cognitive demands rather than amplify them (Feilke & Rezat, 2020; Krabbe, 2023). In this sense, the fragmented structure and procedural scaffolds may free up cognitive resources for dealing with the task's content rather than surface-level text production.

Overall, the findings suggest that structural and linguistic design changes do not automatically result in a higher cognitive load. Instead, they appear to reorganise cognitive demands in a way that maintains overall mental effort at a comparable level (Krieglstein et al., 2023). From an instructional perspective, this implies that reworked documentation formats with a clearer structure and language can be incorporated into regular classroom practice without overwhelming students cognitively. However, the present data only address perceived overall cognitive load. Ongoing and future analyses will therefore examine students' protocol structures and their use of language scaffolds in more detail. Particular focus will be given to the separation of observations and interpretations, the linking of data and interpretations, and the development of data-based arguments.

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Potential Of ChatGPT As A Pedagogical Tool In Biology Education: Enhancing Student Engagement And Critical Thinking

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The integration of Artificial Intelligence (AI) in education has transformed learning processes, with ChatGPT emerging as a valuable pedagogical tool. The objective of this study was to analyse how ChatGPT could enrich the educational experience, promoting engagement, reflection and development of critical skills among students. Conducted in a state school in Diadema, São Paulo, Brazil, the research involved a first-year high school class (N=20) engaging in structured activities using ChatGPT. Students formulated questions, interacted with the AI, and completed a questionnaire assessing their perceptions. Results indicate that initial AI usage was superficial, with students seeking direct answers rather than engaging in critical inquiry. However, as the activity progressed, students developed more complex and reflective questions, demonstrating deeper engagement with the subject matter. Post-activity questionnaire responses highlighted a shift in AI usage, with students recognizing ChatGPT as a research tool rather than a means for effortless answers. Despite ChatGPT's benefits, the study underscores the irreplaceable role of teachers in guiding students toward meaningful learning. Teacher mediation was identified as essential for fostering critical thinking, refining questioning skills, and contextualizing AI-generated content. The findings reinforce the importance of balancing AI integration with human interaction, advocating for pedagogical strategies that leverage technology while maintaining teacher-led inquiry-based learning. Ultimately, this research highlights AI's potential to enhance education while emphasizing the necessity of teacher involvement in knowledge construction.

Keywords: Artificial Intelligence, Critical Thinking, Science Education.

Introduction

The integration of technology in classrooms has gained significant space in recent years, with emphasis on the use of Artificial Intelligence (AI) tools. Among these, ChatGPT (Generative Pre-trained Transformer), a language model developed by OpenAI, emerges as an ally in the teaching and learning process. Launched in 2019, ChatGPT is based on a large language model technology and uses Reinforcement Learning with Human Feedback (RLHF) to interact naturally with users, offering personalized responses and immediate feedback on tasks (Cano; Venuti; Martinez, 2023). However, it's use requires caution, since meaningful learning is based on the principle of constructing onw's one and personal meaning in relation to knowledge and learning situations, which demands understanding, analysis and critical reflection (Coll; Sole, 2006; Gomes; Frank; Rocha, 2020).

In addition, there is a risk that students might become excessively dependent on the tool, compromising the development of critical and emotional skills. Božić (2023) highlights that AIs can reduce face-to-face interactions and negatively affect students' emotional and social development. There is also a need to verify the accuracy of the information provided by the AI, as errors can occur. That said, even with the advantages of AI, it's evident that the role of the teacher remains essential. In addition to teaching academic content, the teacher collaborates with

the development of students' social, emotional and cultural skills.

Barreira, Moura-Silva, and Gonçalves (2024) emphasize that the use of AI should be complementary, helping teachers to deepen learning processes and students' socio-emotional development. The teacher also plays a crucial role in teaching students to ask questions and develop opinions, promoting autonomy and critical thinking. According to Farace (2024), it is up to the teacher to establish the connection between the content provided by AI and the individual experiences of students, promoting more integrated learning.

From a pedagogical perspective, the use of generative AI tools can be situated within the framework of active methodologies mediated by technology, which emphasize student protagonism, inquiry, and intentional teacher mediation (Araújo et al., 2025). In this view, digital technologies do not inherently promote meaningful learning; rather, it is the teacher's critical mediation that organizes, guides, and gives pedagogical meaning to students' investigative processes. This understanding aligns with research on interest development, which highlights that learners' engagement can evolve from situational interest toward more enduring forms of individual interest when students are encouraged to explore self-selected questions within a shared learning context, involving both affective and cognitive dimensions (Hidi & Renninger, 2006). Together, these perspectives help frame inquiry-oriented activities supported by generative AI as learning environments in which meaningful engagement may emerge through the combination of personal interest, structured inquiry, and teacher mediation.

The main aim of this study was to explore how upper secondary students interact with a generative AI tool (ChatGPT) during an inquiry-oriented Biology activity, and how teacher mediation influences the depth and nature of this interaction. Rather than evaluating learning gains or content mastery, the study focused on understanding students' inquiry behaviours, including the formulation and refinement of questions, the use of AI-generated responses, and students' perceptions of the role of the teacher in this process.

More specifically, the study sought to examine whether students' initial use of ChatGPT, often characterized by direct answer-seeking, could evolve toward more reflective and exploratory forms of questioning when embedded in a mediated classroom activity.

Based on these aims, the study was guided by the following research questions:

1. How do students formulate and refine questions when interacting with ChatGPT during an inquiry-based Biology activity?
2. What changes can be observed in the nature of students' interactions with ChatGPT throughout the activity?
3. How do students perceive the role of teacher mediation in supporting meaningful use of generative AI in the learning process?

These questions were intentionally framed in an exploratory manner, consistent with the short duration of the intervention and its implementation in a single classroom session. Accordingly, the study does not aim to establish causal relationships or generalizable outcomes, but to generate situated insights that can inform future research and pedagogical practices involving the integration of generative AI in science education.

Methodology

Activity Design And Procedures

The study was conducted in a public state school located in Diadema, São Paulo, Brazil, with a first-year high school class composed of approximately 20 students, aged between 15 and 16

years old. This educational stage was selected because the topic Fungi is formally introduced in the biology curriculum at this level. The theme involves abstract biological concepts, such as structure, reproduction, ecological roles and symbiotic relationships, that often require a deeper conceptual understanding to support knowledge construction. Consequently, students require pedagogical support to actively relate new information to pior knowledge, establish conceptual and personal connections and engage in explanatory reasoning to construct scientifically grounded understandings. In this context, the use of Artificial Intelligence was included as a mediating digital tool to support and stimulate the access to scientific information, aligned with the teacher guidance in fostering reflective and meaningful learning processes.

Rather than testing predefined learning outcomes, the proposal sought to understand changes in student's questioning behaviour, use of ChatGPT, and perceptions of teacher mediation. The activities took place in the school's computer laboratory. It is important to highlight that, prior to the start of activities, a survey of the student's prior knowledge was conducted through a word cloud built based on what the students associated with the topic of fungi. This word cloud was organized on the blackboard. The central activity was structured in three main stages, with students organized in pairs for the first and second stages.

A) Stage 1: Question formulation (20 minutes)

Students were asked to formulate general and specific questions related to the theme Fungi, starting from de guiding question "What are fungi?". There were no explicit instructions on how to ask those questions at this point.

B) Stage 2: Guided interaction with ChatGPT (20 minutes)

Students used the ChatGPT to seek answers to their questions and deepen their knowledge. The teacher acted as a mediator, encouraging students and emphasizing investigation, exploration and reflection rather than the search for direct answers.

C) Stage 3: Questionnaire (individual)

At the end of the activity, the students completed a questionnaire specifically designed to identify their perceptions of: before using ChatGPT, their interactions with the AI tool and the difference before and after the activity, the teacher's role during the activity, and their own expectations regarding the future use of ChatGPT for learning purposes.

Data Collection And Analysis

Data were collected from two main sources, the questions formulated by students during ChatGPT interaction and the questionnaire. The collected data were analyses using a quali-quantitative approach. Qualitative data consisted of the questions formulated by students during the second stage of interaction. These questions were initially red and grouped according to their thematic focus, based on the biological content, that were organizes in three categories:

1. Structure and Reproduction of Fungi;
2. Ecological Interactions and Health Impact;
3. Applications and Uses of Fungi.

The categorization made it possible to identify how the students searched for different dimensions of the subject during their guided interaction with ChatGPT, navigating from structural and reproductive aspects to ecological roles and practical applications.

Quantitative data from the questionnaire were analysed descriptively using absolute frequencies.

Qualitative and quantitative results were interpreted together to identify consistencies between

student´s reported perceptions and their observed questioning behaviour.

Results And Discussion

In the first stage of the activity (question formulation), students initiated their interaction with ChatGPT by asking the question "What are fungi?". As expected, the AI-generated responses were very similar, given the uniformity of the initial prompt. For this reason, these responses were not transcribed.

Prior to the intervention with teacher's mediation, students tended to use the tool superficially, obtaining quick answers or through "copy-and-paste" practices. This was noticed in the first stage, as students asked direct questions and didn't engage in follow up questioning, and directly address to research question 1, regarding how students initially formulate and refine questions when interacting with ChatGPT.

In the second stage (guided interaction with ChatGPT), students worked in pairs to formulate their own questions so they could deepen their understanding of fungi. The questions generated during this stage were grouped into three categories (Table 1).

Table 1. Questions asked to AI during the second stage of the research, later categorized.

Category	Questions
1. Structure and Reproduction of Fungi	What are hyphae and mycelium?
	How is each fungal species formed, and what characterizes them?
	What does sexual and asexual reproduction mean?
	Do fungi create genetically similar clones?
2. Ecological Interactions and Health Impact	Why are fungi so ecologically important?
	What are beneficial symbioses?
	Where can parasitic fungi be found, and how can they be identified?
	Why are some fungi pathogenic?
	Why are some diseases are caused by fungi?
3. Applications and Uses of Fungi	How are fungi used in medicine?
	How can fungi be used in food production?
	So, is the bread we eat made by a fungus?

After the intervention, student's demonstrated a more reflective and in-depth use of ChatGPT as an ally to the learning processes, characterized by the elaboration of more complex questions and detailed research, with a more sustained inquiry process, that suggests the increased curiosity, engagement and interest of the students.

In the first two categories above, although the questions were not very reflective and still focused on conceptual understanding, some went beyond basic concept definition. For example: Do fungi create genetically similar clones? (category 1) and Where can parasitic fungi be found, and how can they be identified? (category 2). These can indicate the effort to explore mechanisms, processes and applications of Fungi. In the third category, several questions were connected with student's everyday experiences, providing a more reflective perspective, such as food

consumption and health. Here we observe that as the guiding teacher encourages more reflective questioning, students will have the opportunity to learn how to ask new questions, and enhance their inquiry skills (Farace, 2024).

Four of the ten questions involved in the third stage (questionnaire) were selected for these discussion. Of the 20 students, 17 responded to the questionnaire. In the first question ("Had you ever used Chat GPT before this activity?"), 16 students reported prior use of ChatGPT, which was expected given the frequent exposure to digital technologies nowadays. Even though current generations were born in contact with technology, this familiarity does not necessarily indicates effective or critical use of those digital tools such as ChatGPT.

The second question addressed the main differences students noticed in using Chat GPT before and after this activity. Three representative literal responses were selected for analysis: *"Now I've stopped cheating and started using it as a research tool"*; *"I stopped getting answers and started asking"*; and *"Before, I only got the answer to the activities; today I was able to study through it to learn and not just copy what is written."* These responses suggest that students began to understand the importance of moving beyond the mere reproduction of the contents toward seeking more connections, and constructing understanding, align with the meaningful learning processes proposed by Coll and Solé (2006).

In the third question ("Do you think that the teacher can be removed from this activity, so you (students) would do the activity alone?") of the 17 answers obtained, 16 considered the teacher's presence essential, while one student reported not understanding the question. Two highlighted literal answers were: "No, because the teacher is there to guide and teach" and "I think it is good for the teacher to advise the students in the activity". These answers indicate that the students realize the importance of the teacher's role as a mediator, who supports active learning, and not as the source of answers, which aligns with Barreira, Moura-Silva, and Gonçalves (2024), that emphasizes the teacher's role in the knowledge construction fostering critical questioning, although, unfortunately, teacher education programs often does not prepare them adequately to carry out this mediation role (Nóvoa, 2017)

In the fourth question ("Do you think your way of interacting with ChatGPT will change from now on?"), 13 students said that they believed their interaction would change, while four disagreed and said that wouldn't change. Statements such as "Use for research and not for cheating" and "I will dive deeper and create more questions instead of just getting simple answers." indicate that students understood the purpose of the activity as an opportunity to investigate and learn, rather than merely reproduce information. Some responses highlight the relevance of teacher mediation supporting high-quality questioning and knowledge construction such as: "More detailed and specific question", "I would change to try to understand the lessons, for example, ask questions about the doubts I have about the activities" and "Now I know how to ask the right way".

Although ChatGPT does not always responds with the adequate concept and knowledge, it is possible to reduce the chance of errors when formulating good questions. As for good questions, we consider that the more the teacher encourages the student to be reflective and critical about a given subject, the more these questions will be improved in terms of quality (Farace, 2024). These responses relate to research questions 2 and 3, particularly regarding changes in interaction patterns and student's perceptions of teacher mediation. In some way, ChatGPT's clarity and accessibility contributed to more meaningful learning, reinforcing its usefulness as a complementary tool. However, the study also underscores the importance of teacher mediation, as highlighted by Barreira, Moura-Silva, and Gonçalves (2024), who point out the irreplaceable

role of educators in guiding the learning process. These findings can be interpreted considering interest-driven learning perspectives, which emphasize the role of student's personal interests in fostering deeper engagement and inquiry (Hidi & Renninger, 2006).

This study presents limitations that should be considered. First, the intervention was conducted with a single class, involving a limited number of participants, which restricts the possibility of statistical generalization. Second, the activity took place during one class session, which constrains the observation of longer-term learning processes and the consolidation of inquiry practices supported by generative AI. In addition, the study was carried out in a specific public-school contexto, in Brazil, characterized by particular curricular, institutional, and temporal conditions. As a result, these findings should be understood as context-dependent and illustrative of possibilities rather than as representative of all educational settings or student populations.

Therefore, the results do not aim to establish any causal relationships or universal claims about the impact of ChatGPT on learning. Instead, they indicate tendencies and patterns of interaction that emerge when generative AI is integrated into an inquiry-oriented Biology activity with explicit teacher mediation. These limitations are consistent with the exploratory nature of the study and support a cautious interpretation of its scope and applicability.

Conclusion

This study reinforces that ChatGPT can be a powerful educational support tool, as long as used in a critical and mediated manner. Its capacity to personalize content and provide clear answers makes it a valuable resource for enriching the educational process. However, teacher mediation remains essential to ensure that interactions are meaningful and aligned with learning objectives. In this perspective, the teacher is understood as a mediator and collaborator, not a transmitter of knowledge. However, to assume this mediating role, it is necessary to disengage from the traditional conception of teaching and focus on the process of knowledge construction. This highlight the need for teachers to reflect on their conceptions of science, learning and education, which should be addressed in teacher training courses.

The integration of artificial intelligence in education also raises ethical and cultural challenges that demand continuos reflection and adaptation. Moreover, the new learning culture requires that teachers and students to develop critical thinking, soft and digital skills, fostering a more inclusive and meaningful education. Within the context of this study, the use of ChatGPT appers to have contributed not only to development of critical and investigative skills, but also to increase student engagement and interest, expanding the possibilities of integrating AI in various disciplinary contexts. This work emphasizes the importance of balancing technology and human interaction, pointing out ways for a more innovative and inclusive education.

From a methodological standpoint, reflective and critical reading and writing activities related to the topic of fungi could have been carried out prior to the use of the AI tool in this specific context. Such an approach might have provided students with conceptual and argumentative references that would enable them, under teacher mediation, to engage in a more critical, conscious, and problematizing dialogue with the artificial intelligence.

In this perspective, it's interesting to consider for further research these reflective and critical reading and writing practices as pedagogical actions that might precede the use of generative AI, that's because it highlights the central role of intentional teacher mediation in shaping students' interactions with such tools. This understanding supports the relevance of comparative designs that explicitly examine the presence or absence of teacher mediation, as well as investigations into teachers' pedagogical beliefs and professional development. Together, these lines of inquiry

may contribute to the development of evidence-based guidelines for the responsible, critical, and pedagogically grounded use of generative AI in science education.

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How To Teach Science To 3-6-Year-Old Pupils: Pre-Service Teachers' Perceptions Of Immersive Training With 360° Classroom Videos

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The paper explores how immersive training using 360° classroom videos can enhance science education for children aged 3-6. In France, future primary teachers, often with limited scientific backgrounds, receive minimal science education during their Master's-level training, which poses challenges for teaching science effectively. To address this, the study investigates the perceptions of pre-service and early-career teachers regarding immersive 360° video training as a tool for improving their pedagogical approaches. The training involved two phases: a 2D workshop presenting a lesson on buoyancy and an immersive 360° session using a Quest headset. The 360° session featured augmented content and a sequence based on the children's book Plouf to explain the concept of pulleys. Ninety-four participants, primarily inexperienced teachers, evaluated the training through pre- and post-session questionnaires. Findings reveal that 73.3% found the 360° videos immersive, with key elements like spatial exploration and audio ambiance enhancing engagement. Over 74% felt the training significantly improved their understanding of scientific criteria, while 66.7% reported increased motivation to teach science through inquiry-based methods. However, 68% of participants experienced physical discomfort during 360° sessions, indicating room for improvement. The study highlights the potential of immersive tools such as 360° videos to bridge the gap between theory and practice in teacher training. Future research will compare the effect of the order of the two session modalities offered to students on their appropriation of the targeted elements of scientificity and perception of the 360° modality.

Keywords: Immersive Teacher Education; Science Education; 360° video

Introduction

This paper explores how immersive training using 360° classroom videos can support science education in early childhood (ages 3–6). In France, future primary school teachers, many of whom have limited scientific backgrounds, receive relatively little training in science education during their Master's programs. This situation is particularly problematic given that international assessments consistently highlight significant difficulties in science learning among primary school pupils (IAEEA-TIMSS, 2024; OECD-PISA, 2025). Furthermore, opportunities for trainee teachers to observe science teaching practices in kindergarten classrooms are rare, and existing practices are often misaligned with curricular expectations (Cavaillès et al., 2023).

In response to these challenges, this study examines the potential of immersive technologies to enhance teacher education in science. More specifically, it focuses on the perceptions of pre-service and early-career teachers regarding the use of 360° classroom videos as a professional training tool, and on how such environments may help them better appropriate key elements of the scientific approach in early childhood education.

The training program was designed around two complementary modalities. The first consisted of a trainer-led workshop in which excerpts from a kindergarten science lesson on buoyancy, filmed using 360° video, were projected onto a conventional 2D screen. The second modality involved an immersive 360° session using a Quest headset, combining classroom environments with augmented pedagogical resources. This 360° sequence was based on the picture book *Plouf*

(Philippe Corentin, 1991) and aimed to introduce the principle of the pulley (Blanquet, 2010; MEN, 2023). Across both modalities, the training emphasized the explicit formulation and analysis of scientific criteria, such as the primacy of experimentation, reproducibility, and the robustness of experimental setups (Blanquet & Picholle, 2016).

The design of this training sequence draws on research suggesting that immersive and contextualized learning environments can support professional learning by fostering situated understanding, engagement, and transfer to practice (Degeuse & Sénécail, 2025; van den Beemt & den Brok, 2019). Studies have also shown that immersive technologies can enhance learner motivation and knowledge acquisition (Bower et al., 2020). In the field of teacher education, 360° video has been identified as a particularly relevant tool for providing authentic classroom experiences and supporting professional vision (Qian, Shang & Qin, 2023). However, despite growing interest in immersive video for teacher training, relatively few studies focus on specific subject areas (Roche, Rolland & Cunningham, 2023), and even fewer address science education in early childhood contexts (Tan, Wiebrands, O'Halloran & Wignell, 2020).

Building on this gap, the present study investigates how pre-service and early-career teachers perceive immersive 360° video-based training for teaching science in kindergarten.

Context and Theoretical Framework

In France, future primary school teachers are trained to teach pupils aged 3 to 11, and are recruited on the basis of a regional competitive examination at Master's level. Training institutes within universities offer Master's-level courses dedicated to the training of these teachers, the content of which is defined by the Ministry of Education at national level. Even though most of the students in these Master's programs do not come from scientific backgrounds, and the results of international tests show that primary school pupils have major difficulties in science, their training in science teaching is very limited (32 hours in all over the course of the Master's program). The situation is such that it's also difficult for them to observe teachers doing science particularly at Kindergarten level, as the latter are rare and their practices are rarely in line with expectations.

This paper addresses the critical need to enhance science education in early childhood (3–6-year-old) by empowering teachers with innovative teaching approaches, specifically utilizing 360° videos to foster engaging learning environments that stimulate curiosity and critical thinking through the analysis of in situ situations filmed in classrooms with teachers. Indeed, the teaching plan that we designed aims to equip future and in service teachers with the necessary skills to implement scientific criteria in their daily practices.

Researchers suggest that immersive technologies, provided with authentic and contextualized learning experiences, can enhance training (Milgram et al., 2020; 1995). The benefits of virtual immersion in education are varied: it offers variety to teaching methods, encourages situated learning, facilitates transfers to professional environments… (Dunleavy & Dede, 2014; Mellet-d'Huart, 2021, Walshe & Driver, 2019; Theelen, van den Beemt & den Brok, 2019). Moreover, research shows that interacting with these technologies stimulates student engagement and motivation, and improves knowledge acquisition (Slater, 2017; Bower et al., 2020). Regarding 360° video, it is considered an effective tool for assessing professional engagement, providing future teachers with immersive experiences closer to reality (Roche & Rolland, 2020; Qian, Shang & Qin, 2023). The potential of interactive video as a learning tool seems to be a real enabler, emphasizing its role in actively engaging students and improving cognition and attention (Altinpulluk, 2019; Merkt & Schwan, 2014). However, only few studies focus on a specific subject-matter (Roche, Rolland & Cunningham, 2023), and fewer on science education (Tan,

Wiebrands, O'Halloran & Wignell, 2020).

Research Questions

While 360° video immersive learning environments have been explored in terms of engagement, motivation, and professional development, little research has examined their perceived benefits and challenges for teaching science in preschool education. Although our study encompasses a broader analysis of the impact of 360° training, this paper specifically focuses on how teacher trainees perceive its effectiveness in supporting science instruction in early childhood settings.

Method and Design

We designed a two-phase training program using two different modalities:

- A trainer-led workshop based on extracts from a learning sequence on the concept of buoyancy filmed via 360° and projected onto a conventional 2D screen.
- A virtual reality training session (Quest headset) featuring hybrid resources: interactive environments with augmented documentation and a detailed presentation of a learning sequence, based on the picture book *Plouf* (Philippe Corentin, 1991), to explore the principle of the pulley.

Each phase was designed to include the presentation of the science sequence in kindergarten, with the emphasis on the teacher's explicit formulation of elements of the scientific approach, while providing a definition of these elements (testing reproducibility, the robustness of an experiment, the primacy of the experiment, etc.).

To assess the impact of the training sequence on perception and knowledge acquisition, students followed one of two pathways: either starting with the 2D workshop before moving on to the 360° training or reversing the order by beginning with virtual reality before engaging with the 2D workshop. The training was conducted six times with master's level students, totaling 94 participants (Table 1.), about half of whom (51) were very-early-career teachers.

Table 1. Participants.

		Preservice Teachers	Early Career Teachers
Age Average		24	35,7
Population		43	51
Gender	Male	11	8
	Female	32	42
	Other	-	1
Average teaching experience alone		Less than a week	Approximately three months part-time

Among those who had already taught, their teaching experience was very limited (only a few months at most), and very few had worked in preschool settings.

When it comes to their exposure to early childhood education, 80.9% reported having observed preschool classrooms, but only 42% had ever seen science being taught in these settings. When science activities were observed, they were primarily focused on biology, with an emphasis on hands-on activities, plant-related topics, and questioning strategies.

Questionnaires were distributed before the training sequence and after each phase (2D and 360°). The first questionnaire aimed to assess students' familiarity with immersive technologies as well as their initial conceptions of scientific criteria. The two subsequent questionnaires focused on gathering their perception of the training they had just completed, evaluating their sense of self-efficacy, and measuring their progress in understanding the definitions of scientific criteria. For this paper, we choose to focus exclusively on the question of pre-service and in-service teachers' perception of the 360° training.

Findings

Perception Of The 360° Experience And Setup

Overall Satisfaction

Figure 1. Global satisfaction concerning the immersive training.

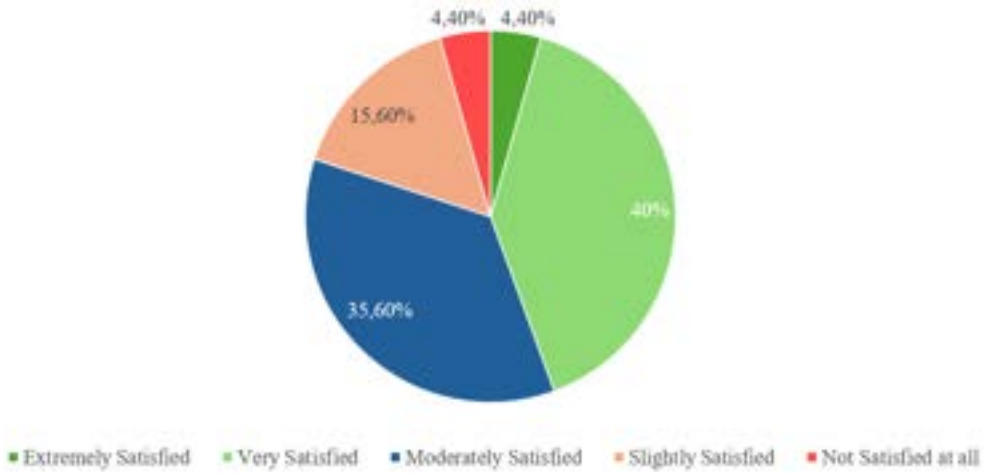
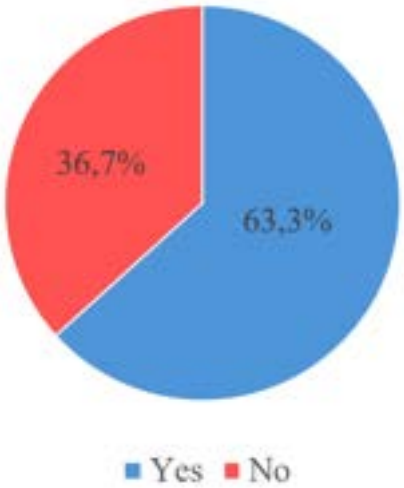


Figure 2. Participants' willingness to recommend the training to pairs.

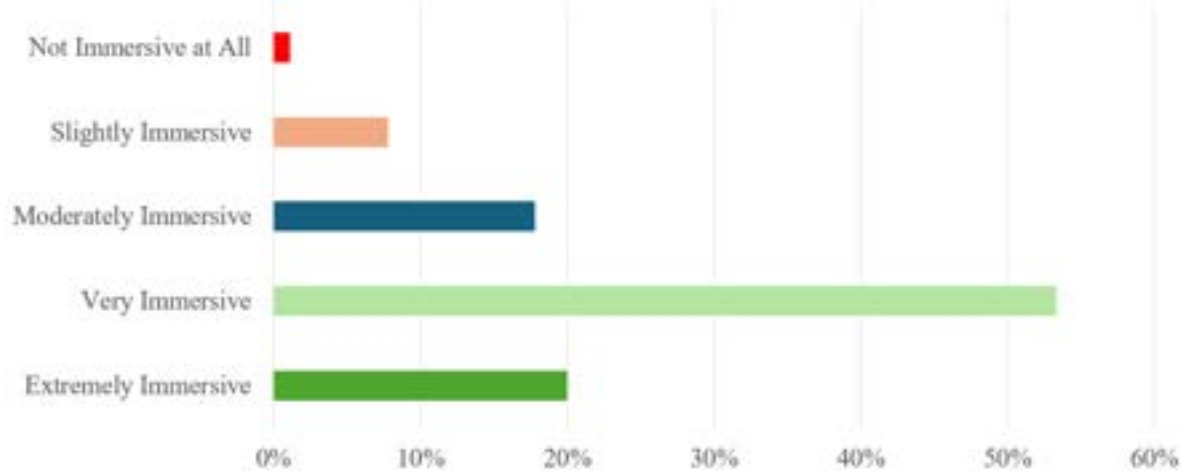


The results (Figures 1 and 2) show that 44.4% of the participants were extremely or very satisfied with the immersive training, while 35.6% rated it as moderately satisfying, which is an engagement with the experience. On the other hand, 20% expressed lower satisfaction, which is an opportunity to further improve the training in order to meet the expectations of the participants.

Similarly, 63.3% of participants would recommend this training to others, reflecting overall positive feedback. While some did not feel inclined to recommend it, this provides valuable insights for potential improvements to make the experience even more impactful.

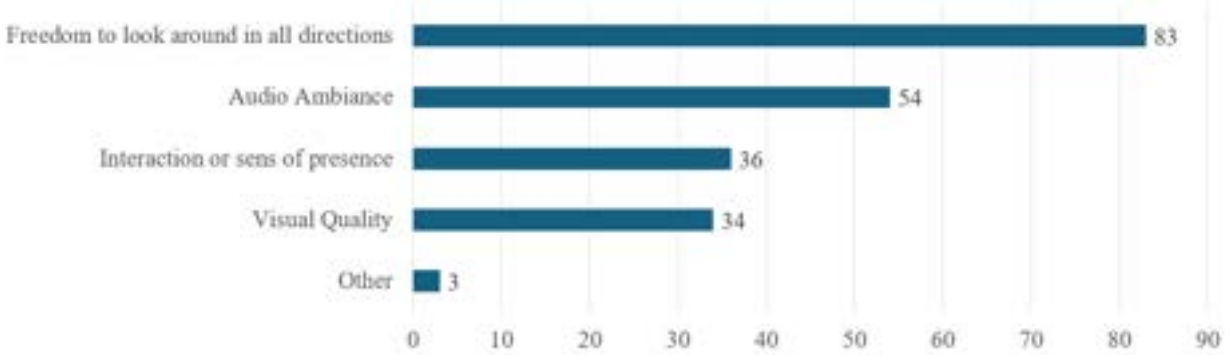
Immersion

Figure 3. Perceived level of immersion in the 360° video.



Most participants (73.3%) found the video very or extremely immersive (Figure 3), confirming its strong impact. With 17.8% rating it as moderately immersive and only 8.9% as slightly or not immersive, the experience was generally engaging.

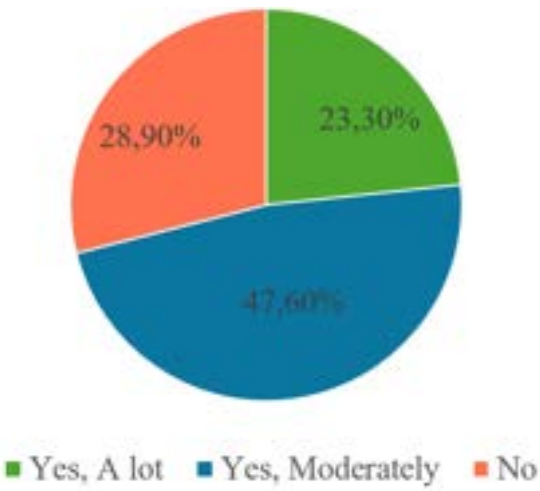
Figure 4. Aspects contributing to participants' sense of immersion.



The key factor enhancing immersion was the freedom to look around (83 responses), followed by audio ambiance (54) and visual quality (34). Interaction and sense of presence (36) also contributed, while only 3 participants mentioned other factors (Figure 4). This highlights the importance of spatial exploration and sound in creating an immersive 360° experience.

Furthermore, when asked whether the use of 360° video led to better engagement, the majority 71,2%) responded yes (Figure 5).

Figure 5. Perceived impact of the immersive format on participants' engagement with the content.



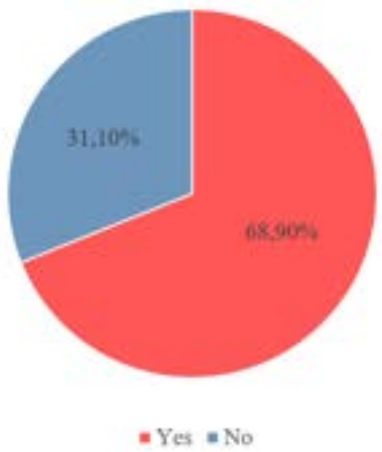
When asked about the reasons for their increased engagement (Table 2), participants emphasized the importance of immersion, particularly through a sense of involvement (10) and being in a science classroom (9). They also highlighted better concept understanding (6), stepping into the teacher's role and perspective (10), and connecting theory to practice (5). Technological affordance and freedom of navigation (4) further reinforced the immersive experience, making it a key factor in engagement.

Table 2. Categories related to participants' perceived reasons for increased engagement.

Category	Count
Sense of involvement/engagement	10
Immersion in a science classroom	9
Better understanding of the concepts at play	6
Projecting oneself into the role of a science teacher	5
Stepping into the teacher's perspective	5
Connecting theoretical content to real-world practice	5
Putting oneself in the place of a student	4
Technological affordance	4
Freedom of navigation and choice / autonomy	4

Nevertheless, physical discomfort emerged as a major obstacle (68.9%) to students' well-being during the 360° session (Figure 6)

Figure 6. Participants' reported physical discomfort.



Perceived Efficacy

The vast majority of students (96.6%) said they were able to identify the elements of the scientific approach targeted in the videos (360° session) and 74,4% that the session contributed enormously or a lot to their understanding of these elements. 66,7% considered that the 360° session enhanced their motivation to teach using the scientific inquiry approach.

Figure 7. Perceived contribution of the videos to understanding scientific criteria.

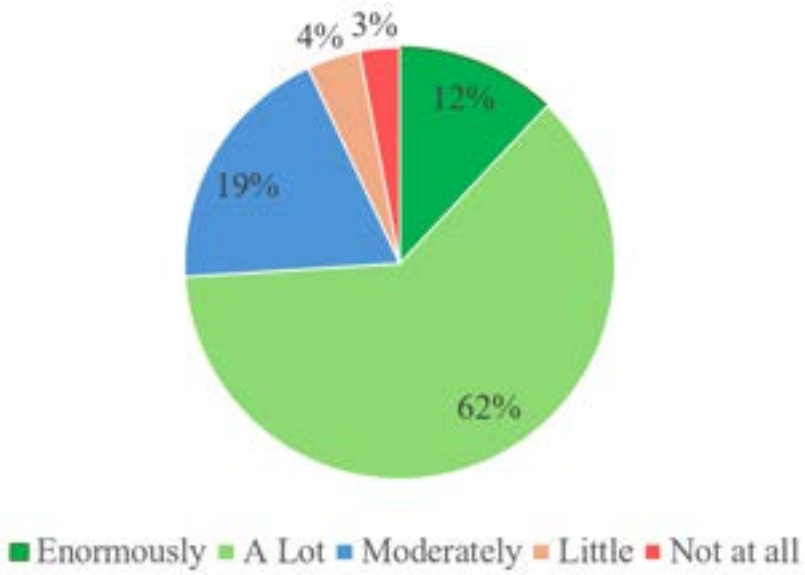
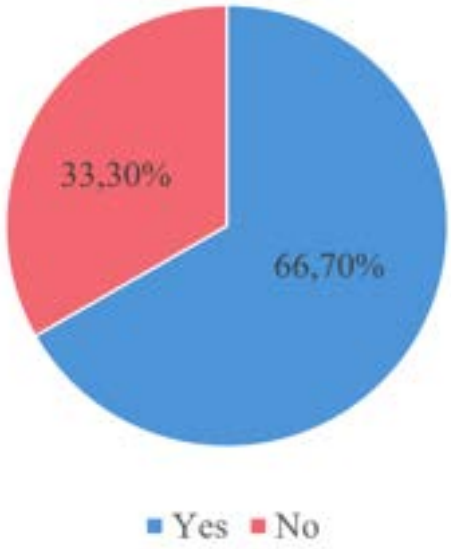


Figure 8. Perceived impact of the immersive experience on participants' motivation to teach the scientific method.



Discussion and Implications

Such results reinforce the idea that 360° videos (at least according to 74.4% of respondents) could enhance the learning of scientific criteria. It corresponds to the previous findings regarding the degree of engagement or immersion affected such aspects as the liberty of exploration in the environment (83 responses) and audio ambiance (54 responses), which presumably influenced an increase in conceptual understanding. Only 6.7% said they said there was little or no benefit.

On the other hand, the fact that 18.9% of the participants gave a moderated rating signals that the training, although efficacious, may not suffice for all learners and probably demands further assistance or additional materials for the understanding of the element of scientificity. This is where the instructional design could be improved, for example, by involving more interactive components or guided reflection exercises.

One extension for this study will be a comparison of the two cohorts, those who first have the 360° workshop and those afterwards, to identify and analyse differences between the two. For instance, it could appear that the students who did the 360° session second might be more likely to state that the 360° format adds nothing more than 2D session except for immersion.

The research is ongoing, and data is being processed. A comparison of pre- and post-tests will

also assess how students' knowledge and perception of scientific criteria evolve. This will help measure the impact of 360° training on their understanding and conceptual gains, as well as differences between training groups. Findings will be shared at the conference.

Acknowledgement

The authors would like to thank INSPE Bordeaux (University of Bordeaux), the Immersions 360 en Nouvelle-Aquitaine project, and the POLE PI (Pôle Innovation, INSPE Bordeaux) for their support in developing immersive 360° video resources and pedagogical innovations that enrich teacher education and training practices.

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ESERA 2025 Copenhagen

Learning Through Comics And Students' Stress In Physics: An EDA Approach

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Physics is one of the most challenging sciences to study, and many students find it highly stressful. The significant increase in stress during learning negatively affects the outcomes of the educational process and students' motivation and achievement in physics. The aim of this paper is to explore the potential of educational comics as an instructional approach for reducing students' stress in physics learning. In this paper, we designed and developed two comics on energy topics, presented them to upper and lower secondary school students, and measured their stress levels using modern EDA technology via Moodmetric smart rings. The results showed that using comics in physics instruction significantly reduced students' stress compared to the traditional method. This result is an important indicator for those working in the field of physics education of the importance of providing students with educational scientific comics during learning.

Keywords: Comics, Stress, Electrodermal Activity

Introduction

A new trend in Physics Education Research (PER) is exploring ways to reduce negative emotions, such as anxiety and stress, among students. Comics can be visually stimulating and help alleviate pressures associated with learning complex scientific concepts. The objective is to advance the field by measuring students' stress levels using the Electrodermal Activity (EDA) technique. Prior research is limited in PER. This research aims to contribute to knowledge accumulation in this field.

Stress In Physics Education

According to the theory of emotions proposed by Russel and Mehrabian (1977), the emotional response can be delineated by three factors or dimensions: valency/degree of happiness, arousal/degree of intensity or stress, and dominance/degree of control (Russel & Mehrabian, 1977). However, Bodin and Winberg (2012) recommended the researchers to focus on the arousal or stress dimension. This research will investigate this dimension of the emotion. Citing the seminal Yerkes-Dodson law (1908) stipulates the relationship between stress and performance. This law posits that low levels of arousal lead to diminished performance due to a lack of motivation and concentration. Conversely, high stress can be detrimental to performance due to the onset of anxiety. Moderate arousal is regarded as optimal for peak performance. Molin et al. (2021) have indicated that physics students who experience anxiety or stress are more likely to achieve lower grades than their peers. For instance, students experiencing anxiety may encounter difficulties in regulating their emotions, consequently affecting their performance in physics classes. This may, in turn, result in learning difficulties and underachievement.

Learning Through Comics

The use of comics in science education is not a novel concept. The utilisation of comics is regarded as an efficient medium for conveying scientific concepts and enhancing student engagement. It has been argued that today's students encounter difficulties with extensive reading (Trnova, Trna, & Vacek, 2013), prompting physics educators and experts to devise alternative

methods for the exposition of physics concepts without the need for extensive reading. The use of well-crafted comics has been shown to enhance student interest and comprehension, particularly in physics (Yulianti, Khanafiyah, & Sulistyorini, 2016). Several PER researchers have explored the efficacy of comics in storytelling with university students, leading to a positive impact on both cognitive and emotional domains (Ozdemir, 2017). In research on the use of comics as a medium and content to reduce stress levels and enhance mental well-being, for example, a subsequent study was done by Brand et al. (2019). Also, other studies have explored the efficacy of comics as a pedagogical tool for secondary school students with the objective of enhancing comprehension of physics concepts and fostering greater motivation in the students towards their physics learning (Badeo & Ong Kian Koc, 2021). Research shows that comics positively impact students, but there's a lack of studies on physics education that address their use as stress-reducing tools.

Electrodermal Activity (EDA) In Education

EDA measurements facilitate the assessment of emotional arousal levels, i.e., the intensity of stress. EDA comprises two components: Skin Conductance Level (SCL), which measures long-term emotion and Skin Conductance Response (SCR), which measures short-term emotion (Boucsen., 2012). EDA sensors have been developed to measure stress and reflect an individual's emotional state (Geršak G. & Drnovše J., 2020). The use of EDA sensors is recommended for several reasons. This includes their relatively low cost, a simple and fast physiological response, and easy connection to raw data via Bluetooth, Wi-Fi, the Cloud, or cable (Braithwaite et al., 2013). EDA's applications extend to both laboratory and non-laboratory settings (Picard et al., 2015). However, further efforts are required within the educational sector to leverage the potential of EDA technology to its full potential.

Research Questions

RQ: How do students' average stress levels differ between comic-based and traditional text-based instruction in physics energy topics?

Our study explores the impact of a digital comic on students' energy-related topics, using Moodmetric smart rings to measure stress levels.

Methodology

Participants

The study involved 43 secondary school students (10 females, 33 males) in grades 9-12, who were either learning in English schools or had B2 proficiency, and was conducted in Alexandria, Egypt, in summer 2023.

Research Design

The study used a control-group experimental design. As shown in Figure 1, it has two experimental groups: one got the full version of comics (explanation modules and question modules are in comics), called 'comics-comics' C-C; the other experimental group got a version of comics and texts (explanation modules in comics and question modules are in text), termed 'comics-text C-T'; the control group received the full text version (explanation modules and question modules are in text), termed 'text-text' T-T, for testing.

Measurement Tools

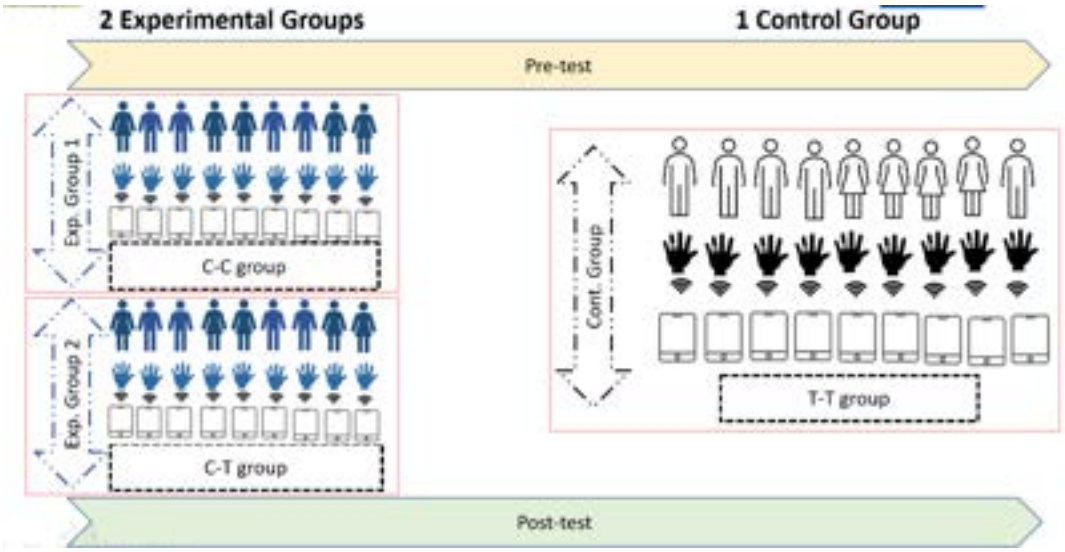
In this research, we used Moodmetric smart rings that measures student stress levels through EDA technique, including EDA/SCR and EDA/SCL per minute. They also measure Moodmetric

MM level, which combines SCR and SCL. Users can monitor stress levels through the app, which displays tension and calm times. These are expressed digitally as an index from 0 to 100, indicating the level of stress (e.g., MM levels 30-50 = moderate stress, <30 = relaxed, 51-55 = elevated stress, ≥56 = significantly elevated stress).

Procedure

We conducted an initial interview with 58 students, and they completed a pre-test on energy. 14 students left the research unfinished, and we had incomplete sensor data for another student. Then, a proportional random sampling was done to get the three groups (one control group and two experimental groups). Three digital learning models were developed: T-T, C-C and C-T. These focused on the same energy topics. All students studied the same content, either in comic or text format, interacted through question modules, and concluded with a post-test. The digital learning and the test were facilitated via a tablet using a dedicated website and occurred in laboratory settings. Students were given a moodmetric smart ring connected to a tablet to record stress which is shown in Figure 1.

Figure 1. Experimental design flowchart.

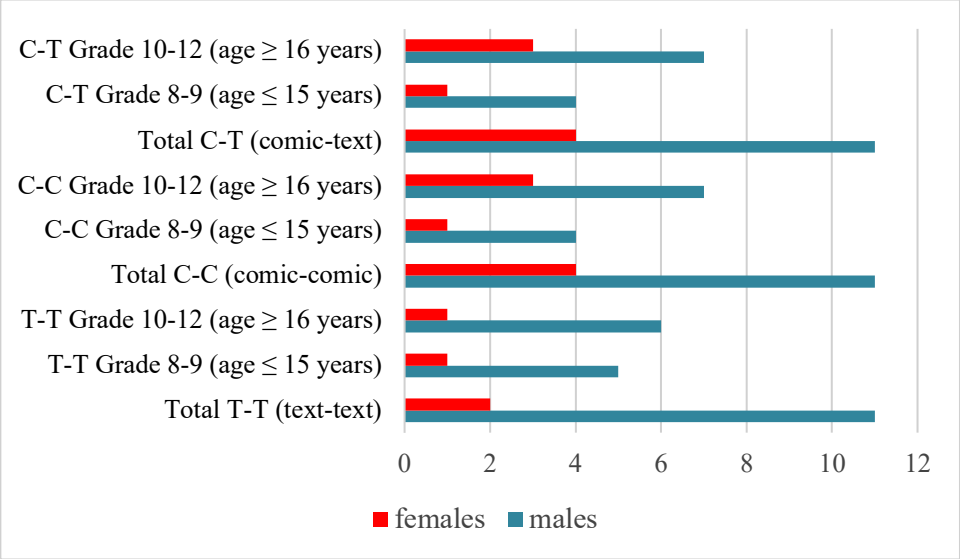


Result and Analysis

Sample Analysis

Figure 2 represents the analysis of the sample. The ratio of students in lower grades (8-9) to those in higher grades (10-12) is lower (12% vs. 23%), though similar across the two experimental groups C-C and C-T. However, in the control group T-T, the percentage of lower graders to higher graders is 14% and 16%. The female-to-male ratio is imbalanced (23% females to 77% males) because most of the volunteer students were learning in boys' schools. Another reason is the conservative Egyptian society, which sometimes stands still. This sometimes prevents girls from participating in research and international projects; however, we shall mention that none of the girls failed to attend and complete all steps of the pre-interview, learning session and post-test, indicating interest and motivation.

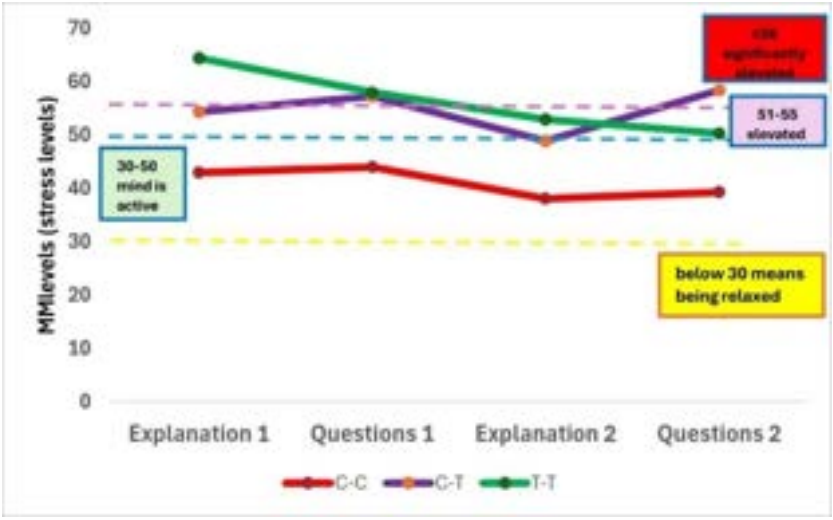
Figure 2: Sample analysis within the three groups according to gender.



Stress Analysis

General descriptive analysis has been done in order to answer the research question. Figure 3 illustrates the mean MM levels, which indicate students' stress levels across the four modules in the three groups. C-C is represented in red, C-T is represented in purple, and T-T is represented in green. Figure 3 shows that the C-C group is below the C-T and T-T groups in the range between 30-50 MM levels, with a moderate stress area for all four modules' explanations and questions. However, the MM levels of the C-T group fluctuate up and down; in the comics explanation modules, the MM levels are lower than in the text question modules, and MM levels go up to reach the T-T group in the first question module or exceed it in the second question module. Furthermore, the T-T group started with high MM levels in the first explanation module and then decreased in the following modules until it reached a moderate MM level in the last module.

Figure 3. Moodmetric MM levels of stress for three groups comics-comics C-C, comics-text C-T, text-text T-T during the four modules.



To test a null hypothesis of "There is no statistically significant difference in the mean stress levels between participants who received the comics-based instructional format and participants who received the text-based instructional format", we applied One Way ANOVA for the three groups, a significant difference F=3.70 *(p=.033) was found.* A post hoc Tukey test determined a

significant difference in favour of the C-C group in comparison with T-T F=19.4 *(p=.026)*. Therefore, we can reject this null hypothesis.

Discussion

This paper aims to answer the research question of how comics impact students' stress levels in physics. The stress line diagram and the observed patterns for the three groups (C-C, C-T and T-T) suggest that the C-C group experienced lower stress during explanations and questions. We can figure out from this study paper that using comics as a tool to present energy content significantly reduces stress levels of students among the C-C group during the learning process, compared with traditional text-based methods. The line graph shows that the T–T group experienced relatively stable high stress levels across all modules, reflected by an almost linear pattern. This may be because the text does not help to reduce students' stress levels, either in explanations or questions, resulting in a straight line with constant flow.

In contrast, stress levels declined in explanation modules and increased in question modules for the C-C and C-T groups. This may be due to the structure of the content itself, rather than the explanations or questions. This can be seen in the C-C group, where the narrative flow of the comics is disrupted by questions. This makes it difficult for students to immerse themselves in the story and escape the tension and stress. Accordingly, stress levels increased in the question modules and decreased in the comic explanation modules. The same pattern is evident in the C-T group, where stress decreases in the explanation modules and increases in the question modules.

The inferential analysis done to test the null hypothesis revealed a significant difference in mean stress levels between the comics-based groups and the text-based group, leading to rejection of the null hypothesis. In other words, the students who received the comics models reported significantly lower stress levels compared to the students who received the text models.

Conclusion

This paper investigated differences in students' stress levels when learning physics through comic-based and text-based instructional formats. Three groups were compared: a comic-comic (C-C) experimental group, a comic-text (C-T) experimental group, and a text-text (T-T) control group. We recognise the reduction in stress when using comics rather than text and when using a complex format combining comics and text.

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Building Bridges: AI Custom Chatbots As Mediators Between Mathematics And Physics

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This study examines the use of AI custom chatbots in educational settings, with a particular focus on the interface between mathematics and physics. Given the growing adoption of AI tools like ChatGPT in learning environments, their potential as personalized tutoring systems is analysed. The study evaluates the impact of AI-generated learning materials on the learning experiences and performance of sixth-grade students, focusing on proportional relationships in mathematical and physical contexts. In a randomized controlled study (N = 214), traditional textbook materials were compared with explanations generated by an AI custom chatbot. The findings indicate that, while the AI-generated materials had an indefinite impact on learning performance, they significantly enhanced positive-activating emotions, situational interest, and self-efficacy expectations, while simultaneously reducing intrinsic and extrinsic cognitive load. These results underscore the potential of AI tools to transform educational practices and to enrich learning experiences. Further research is required to clarify the effects on learning performance and long-term learning outcomes. Overall, the present study highlights the importance of a careful integration and customization of AI tools in order to fully leverage their potential for physics education and related domains.

Keywords: Artificial Intelligence, K-12 Education, STEM Education

Introduction And Theoretical Background

Within current educational research, increasing attention has been directed toward the potential of AI chatbots in educational contexts (Chen et al., 2020). For instance, they can function as intelligent tutoring systems, support research and writing processes, provide individualized feedback, and address specific learning difficulties (Kasneci et al., 2023; Neumann et al., 2024). In STEM fields, chatbots can provide feedback to exercise-related and topic-specific questions (Avila et al., 2024; Liang et al., 2023), opening up new opportunities for the design of learning environments in specialized fields such as physics (Küchemann et al., 2024). While AI-based chatbots offer the potential to provide individualized support across diverse learning situations, empirical evidence regarding their effects on students' learning performance and learning-related experiences remains unclear (Neumann et al., 2024), making it beneficial to assess the potential influence within the context of physics education.

Students' comprehension difficulties in physics lessons are multifaceted – often related to insufficient mathematical skills (Christensen & Thompson, 2012; Leinhardt et al., 1990; Pollock et al., 2007) as well as to challenges in transferring mathematical knowledge to physical contexts (Redish & Kuo, 2015). The causes of these difficulties are not uniform across all students and may arise from misconceptions regarding the physical meaning of ratios, products, or functions (Uhden, 2016). In addition, comprehension problems may arise from difficulties in interpreting and linking multiple representations, such as formulas, graphs, diagrams, and tables (Treagust, 2018). As these representations encode important information, the ability to interpret and

transition between them is considered beneficial for learners (Hansen & Richland, 2020; Opfermann et al., 2017; Treagust, 2018). Targeted assistance in fostering this competence has been shown to enhance students' conceptual understanding (Hansen & Richland, 2020).

Vision-capable AI chatbots, such as ChatGPT, may offer a promising approach in this regard, as they are able to analyse images of representations (Kasneci et al., 2023; Neumann et al., 2024). In this manner, they can provide individualized feedback to support learners in interpreting and linking multiple representations as well as in extracting the encoded information.

Despite the availability of a multitude of chatbots, their effective use in educational settings often requires adaption to specific instructional purposes (Kieser et al., 2023). AI custom chatbots based on existing large language models can be configured to meet such requirements by specifying desired response behaviours, such as the use of situation-specific language or controlled answer length. Moreover, subject-specific knowledge can be incorporated through the integration of relevant instructional materials. Given the current limitations of research in this area, it remains an open question whether chatbots can be used to design suitable learning materials and generate explanations that positively influence students' learning processes. Against this background, the present study investigates the impact of explanations generated by an AI custom chatbot on students' learning experiences and learning performance in physics.

Research Questions

The study is designed as a randomized controlled field study, with students as the target group and is addressing the following key research questions:

How does learning with AI-generated explanations using an AI custom chatbot affect

RQ1: ... emotional aspects?
RQ2: ... situational interest?
RQ3: ... cognitive load?
RQ4: ... self-efficacy expectations?
RQ5: ... learning performance in a mathematical and physical learning context, particularly in terms of the necessary transfer performance to the physical context?

Methodology

Chatbot Design

The AI custom chatbot used in this study was developed on the basis of the model GPT-4.0 and adapted to a specific learning context and target group. The chatbot uses engaging and age-appropriate language, making it suitable for sixth and seventh grade students. Its focus lies on "proportional relationships" as an example of learning with multiple representations, including graphs, tables, and formulas. Students must develop the ability to interpret these representations and transition between them from both mathematical and physical perspectives (Bing & Redish, 2009; Nilsen et al., 2013). To this end, the AI custom chatbot was equipped with subject-specific knowledge and designed to analyse and interpret the different forms of representations in order to provide targeted and individualized feedback.

Nevertheless, it remains open to question whether chatbots are capable of designing suitable learning materials and environments, as well as generating text-based explanations that have a positive impact on the aforementioned constructs. In the present study, the chatbot was employed to provide an AI-generated, text-based explanation of the topic "proportional relationships", based on a textbook overview (Körner, 2020). The explanation was selected according to the following criteria: the accuracy of the content and language, as well as the correct and coherent

use of the three forms of representation – graph, table, and formula.

Study Design

A total of N = 214 sixth-grade students (146 female, 66 male, 2 n.a.) with an average age of 11.7 years (SD = 0.51) at German secondary schools were randomly assigned to an experimental (EG) or control group (CG). Both groups were provided with learning materials on "proportional relationships" which had not been covered in class before. The CG received conventional textbook material, including a topic overview and accompanying explanatory examples. The EG was provided with the same textbook overview but had the examples replaced by a text-based explanation of the topic generated by the custom chatbot.

Immediately following the learning phase, various variables were measured using a four-point Likert scale: the participants' emotions (Pekrun et al., 2011) and situational interest (Linnenbrink-Garcia et al., 2010), the intrinsic and extrinsic cognitive load (ICL and ECL) experienced during learning (Leppink et al., 2013) and the self-efficacy expectation with regard to solving a topic-related task (Jerusalem & Satow, 1999) were assessed. Subsequently, the students completed a self-developed performance test on the "spring scale", which served as an example of the physical concept of proportional relationships.

Data Analysis

The data analysis was conducted using the statistical software R (version 4.4.0). First, the scales used were tested for internal consistency by calculating Cronbach's alpha. The results were acceptable to excellent, and no significant improvements were identified when individual items were removed from the scales. Therefore, the scales were retained for further data analysis. The data was then tested for normal distribution. The Shapiro-Wilk test with a significance level $\alpha = 0.05$ was used to determine the distribution of the data. The results indicated that the data was not normally distributed. The non-parametric Mann-Whitney U test with a significance level $\alpha = 0.05$ was used in the subsequent analysis to identify significant differences between the EG and KG. Cohen's d was calculated to estimate the respective effect size.

Results

The results of the study are summarized below. The complete methodology and results of the study can be found in the publication released in May 2025 (Lademann et al., 2025).

Concerning emotional aspects (RQ1), the EG reported a significantly higher incidence of positive-activating emotions (pleasure and satisfaction) than the CG ($p = 0.00093$, $d = 0.48$, small effect size). Regarding negative-deactivating emotions (boredom, frustration and uncertainty), only a trend could be identified, showing that the CG tended to experience more negative emotions. In sum, the results indicate that learning with AI-generated explanations can have a positive impact on the emotional state of the learners (Figure 1). Regarding the influence on situational interest (RQ2), learning with the custom chatbot's explanation triggered significantly higher situational interest ($p = 0.00223$, $d = 0.45$, small effect size) compared to learning with textbook materials (Figure 2).

Figure 1. Perceived emotions with standard error and level of significance (Lademann et al., 2025).

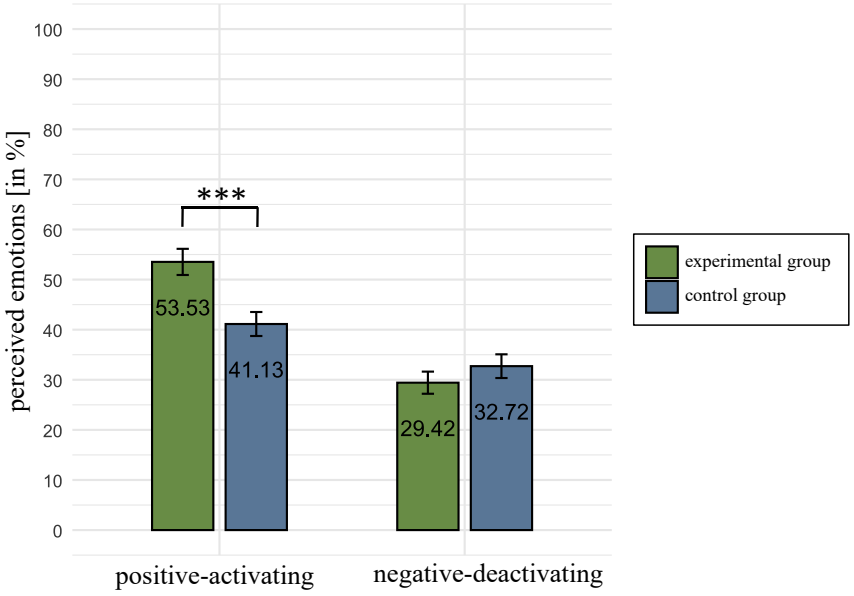
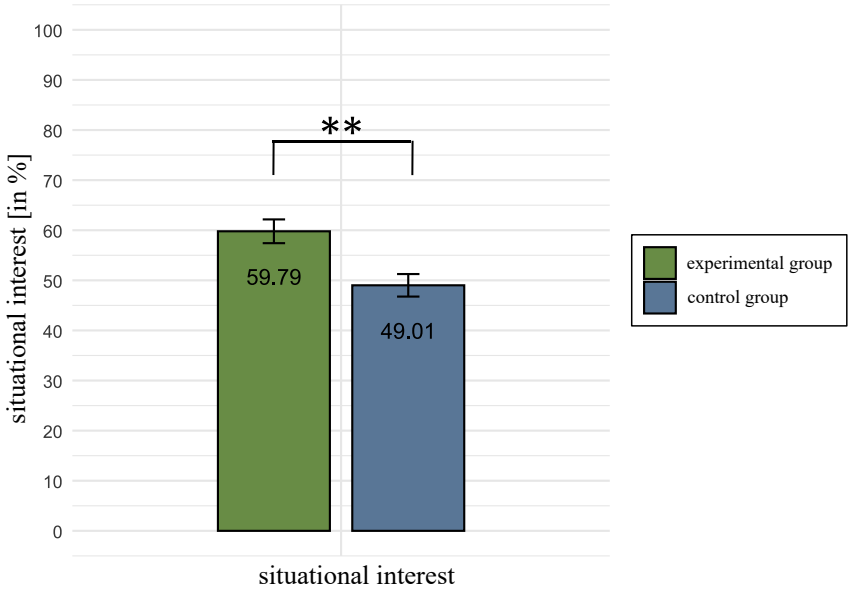


Figure 2. Situational interest with standard error and level of significance (Lademann et al., 2025).



In contrast, ICL ($p = 0.00060$, $d = 0.47$, small effect size) and ECL ($p = 0.0001$, $d = 0.59$, medium effect size) were significantly reduced in the EG (Figure 3). These findings suggest that learning with AI-generated materials diminished cognitive load compared to textbook-only materials (RQ3). Additionally, the EG had significantly higher self-efficacy expectations ($p = 0.00001$, $d = 0.63$, medium effect size) than the CG (RQ4), when it comes to solving a topic-related task (Figure 4).

Concerning the influence on learning performance in a mathematical and physical context (RQ5), no clear trends were identified in the overall result of the performance test or the subtasks. The available data prevents drawing definitive conclusions about the impact of AI-generated materials on learning outcomes compared to traditional textbook materials. After thorough analysis, it was determined that there were no significant differences between the EG and CG in terms of learning performance.

Figure 3. Intrinsic cognitive load (ICL) left and Extrinsic cognitive load (ECL) right, both with standard error and level of significance (Lademann et al., 2025).

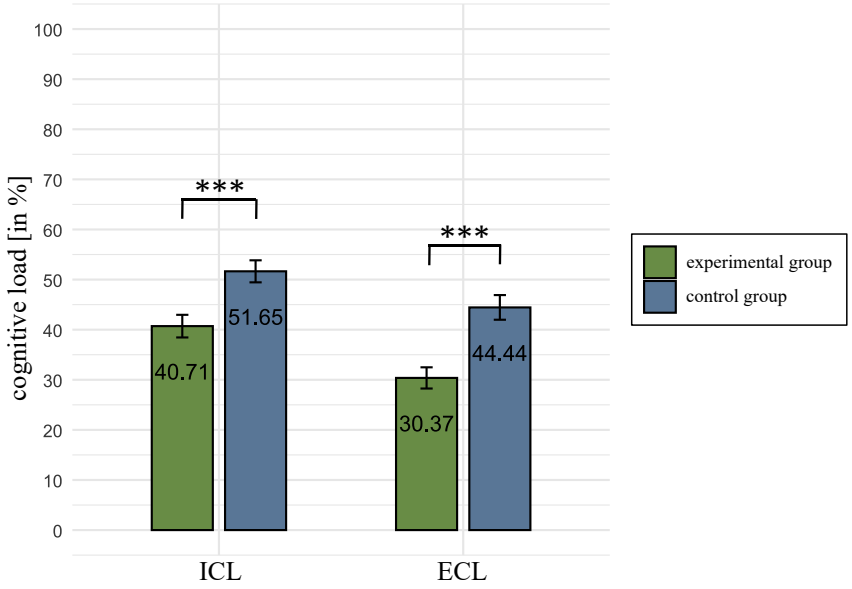
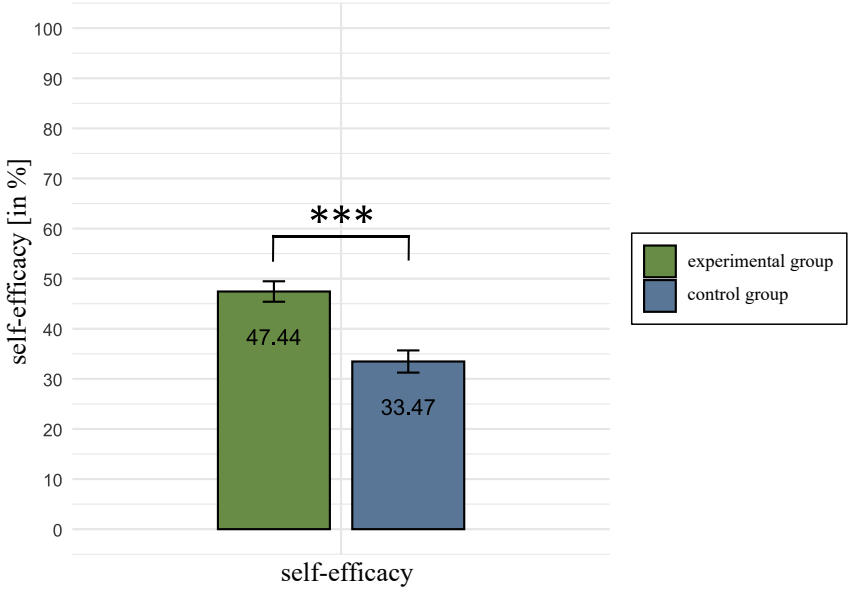


Figure 4. Self-efficacy with standard error and level of significance (Lademann et al., 2025).



Discussion And Conclusion

The results of the present study indicate that learning with materials generated by the AI custom chatbot has a positive effect on the learning experience of students.

The findings indicate that learning with AI custom chatbot-generated explanations, compared to traditional textbook materials, significantly enhances learners' positive-activating emotions and situational interest. The configuration of the chatbot with respect to communicating in a manner intended to encourage and motivate the learner might provide a potential explanation for these outcomes. The motivating tone may have exerted a positive influence on emotions and situational interest.

Furthermore, in comparison to traditional learning with textbook materials, cognitive load was reduced. This could be due to the chatbot's use of accessible language and its conversational and human-like tone. Additionally, the chatbot is adapted to the students' level of knowledge and uses language that is comprehensible to them. Moreover, the EG showed significantly higher self-efficacy, indicating that the explanation of the AI chatbot can foster students' confidence in their

ability to complete tasks. A reason for this may be the encouraging tone of the AI-generated text or the reduced cognitive load, or a combination of both. With regard to learning performance, the data revealed no statistically significant differences. A study comprising a greater number of participants over an extended period of time, in conjunction with individual utilization of the chatbot, has the potential to yield more profound insights.

Several factors limit the generalizability of the present findings, including the relatively small size of the sample, the short duration of the intervention, and the focus on a single topic tailored to a specific target group. Additionally, the learning materials were provided in a centralized manner, which resulted in the lack of consideration of individual differences in material use and the interaction with the chatbot. Consequently, the potential effects of personalized and adaptive feedback could not be examined.

Future research should therefore employ longer-term studies that cover a broader range of topics, and include more diverse target groups in order to validate and extend the findings and assumptions presented here. Moreover, learners should be given the opportunity to interact with the AI chatbot independently to systematically investigate the effects of individualized feedback.

Building on the present results, a subsequent study will conduct a more comprehensive examination of learning outcomes. An optimized AI custom chatbot will be developed, including revisions, refinements, and an adaptation to the didactic framework of the follow-up study. Within a pre-post design, the independent use of the chatbot by students will be examined with regard to its effects on learning performance and the learning experience (emotions, situational interest, cognitive load, self-efficacy expectations), and the technological acceptance of the AI chatbot.

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Part 5 / Strand 5

Nature Of Science: History, Philosophy And Sociology Of Science

Co-editors: *Georgios Ampatzidis & Renee Schwartz*

Part 5 / Strand 5 Nature Of Science: History, Philosophy And Sociology Of Science

Nature of science and its history, philosophy, sociology and epistemology for teaching/learning of science. Includes the significance of models and modelling for science education as reflected in the particular importance attached to the use of metaphors, analogy, modelling, argumentation, explanation, visualisation, simulations, animations and gamifications in science.

Sub-themes:

1) Philosophical Foundations of Science Education
2) The Role of History & Philosophy of Science in Science Education
3) Nature of Science and Epistemic Practices
4) Sociological Perspectives on Science Education

Contents

Strand 5: Nature Of Science (NoS): History, Philosophy And Sociology Of Science 354

Insights Into Physics Students' Lesson Plans On The Nature Of Scientific Knowledge 355

Primary Teachers' Competencies And Difficulties In Teaching Measurement Uncertainty: Pedagogical Challenges Related To Nature Of Science 366

The Growing Need For STEM Careers And The Potential Pathways For Independent Scientists..... 371

Pre-Service Teachers' Engagement Of Scientific Reasoning: Uncovering The Mystery Of Tutankhamun's Iron Dagger 377

How Do Upper Secondary Greek Students View The Nature Of Science? The Case Of Chemistry..... 386

Arguing With Eugenics: Brazilian Reasoning About Inheritance In The Late 1920s 394

Heritage And Transmission: A Reflection On The Origins And Development Of Didactics Of Science/Science Education Research 403

Understanding Of Nature Of Scientific Inquiry (NOSI) In The Early Elementary School Years: Focusing On The Relationship To National Curriculum Standards 412

Strand 5: Nature Of Science (NoS): History, Philosophy And Sociology Of Science

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The strand "Nature of Science (NoS): History, Philosophy and Sociology of Science" explores science as a dynamic human endeavour shaped by historical, philosophical, sociological, and epistemological dimensions. It emphasizes that scientific knowledge develops over time through social and cultural contexts, influenced by human reasoning and interpretation, and highlights how scientific understanding is constructed and validated within the scientific community.

The contributions in this chapter examine developments in science education research with a particular focus on pre-service teachers' and students' understandings of the Nature of Science (NOS) from a broader epistemic perspective, and more specifically on understandings of the Nature of Scientific Knowledge (NOSK) and the Nature of Scientific Inquiry (NOSI). Across the studies, these understandings are explored in different ways: some investigate existing levels of conceptual understanding, while others design and implement instructional interventions aimed at enhancing deeper insight. Some contributions focus on specific dimensions of NOS and NOSI, including the nature of scientific measurement and scientific reasoning. In addition, some contributions draw on the history of science as a pedagogical tool to strengthen understanding of NOS and NOSK, or to promote scientific literacy with an emphasis on social transformation. Overall, the chapter highlights a range of approaches to enhancing how learners and future educators engage with and understand the nature and practices of science.

This chapter aligns with the "Nature of Science (NoS): History, Philosophy and Sociology of Science" strand, contributing to a well-established area of science education research concerned with how learners and teachers understand the epistemological foundations and functions of science. The work aligns with longstanding efforts in science education to move toward developing a deeper understanding of science as a way of knowing, investigating, and explaining the natural world. Epistemically and as a human endeavour, science functions to generate, evaluate, justify, and refine explanations of natural phenomena. Simultaneously, scientific knowledge and practices are recognized as socially and culturally embedded, shaped by prevailing theories and cultural contexts, as well as the values, priorities, and needs of society.

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Insights Into Physics Students' Lesson Plans On The Nature Of Scientific Knowledge

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A program, based on the Lederman's model, was designed to familiarize physics students with the Nature of Scientific Knowledge (NOSK) aspects and its teaching. The program was implemented in Greece during the academic years 2023-24 and 2024-25 and included interactive lectures and workshops. Students' pre-instruction understanding was examined using the VNOS-D+ questionnaire, while their post-instruction integration of NOSK through the analysis of lesson plans. The lesson plans were evaluated for their incorporation of NOSK aspects using teaching approaches such as History of Science (HOS), Scientific Inquiry (SI), and Socio-scientific Issues (SSI). Findings indicate that prior to instruction, students mainly recognized the empirical and tentative nature of scientific knowledge, while other NOSK aspects were often understood in naïve or mixed ways. Analysis of students' lesson plans showed a strong preference for SI alone or in combination with HOS, with students most frequently selecting certain curriculum-related physics topics such as free fall. Although several NOSK aspects were included, the empirical, tentative, and creative dimensions were most successfully integrated. While NOSK was often addressed implicitly, approximately one-third of the students produced lesson plans that demonstrated explicit and reflective integration of NOSK. Overall, the findings suggest that even brief, structured NOSK-focused instruction can support pre-service physics students' initial engagement with NOSK, while highlighting the need for sustained involvement to support effective classroom implementation.

Keywords: Nature of Science, Pre-service Teacher Education, Undergraduate Level

Introduction

Research in Nature of Science (NOS) is fundamental in Science Education, since it is inherent in science and its practices (Lederman et al., 2014). It is also connected to scientific literacy (Lederman et al., 2024) and, regarding science education, the views that students and educators have on scientific research and epistemology (McComas, 2015).

The necessity to integrate the nature of science at all levels of education has been highlighted by many researchers (Erduran & Dagher, 2014; Lederman et al., 2014; Matthews, 2015), and it is already embedded in science curricula in countries like the USA (NGSS, 2013) and New Zealand (https://newzealandcurriculum.tahurangi.education.govt.nz/nature-of-science/5637207725.p). Main reasons for it are enhancing students' active participation, better understanding of science and its epistemic views, comprehension of the differences between science and pseudoscience and the limitations of science as a human endeavour (McComas, 2017, Matthews, 2015).

Teachers and student teachers need to be trained to create effective lesson plans (Mesci & Schwartz, 2017). Teacher training in nature of science is still a matter of research (e.g. Kara & Aslan, 2025; Beeghly, Gao & Kruse, 2025; Sen & Kaplan, 2025; Bugingo et al, 2024) and it seems there is a lot to add in the literature. Towards this direction, the present work focuses on Greek physics students and the results of their training through the analysis of the lesson plans they delivered. In this way, the study aims to contribute empirical evidence to the existing literature by enlightening how physics students engage with the Nature of Science within a traditionally content-focused educational context.

Theoretical Background

Even though researchers agree on the importance of teaching NOS, they don't agree on a widely approved definition and the aspects it consists of (Kampourakis, 2016). There are two main models, the Consensus Model (Lederman et al., 2014; McComas, 2015) and the Family Resemblance Approach (Erduran & Dagher, 2014). Each model has its own advantages and disadvantages, and there is plenty of ink spilled in favor and against each model (Kampourakis, 2016). However, all researchers agree that NOS instruction should be in an explicit and reflective approach, so that students understand it (Bell, 2008; Lederman et al., 2014).

As for Greece, research shows that NOS is not officially integrated in the science curriculum in secondary education, teachers usually do not include it in their instruction and, as a result, high school graduates usually have naïve views of its aspects (Koumara & Plakitsi, 2020). The Greek science curriculum focuses a lot on the scientific content, solving complex mathematical problems and little inquiry work in the science lab. Thus, it is reasonable that senior undergraduate students have limited knowledge of NOS aspects, which also might influence their future approach in teaching science (Abd-El-Khalick & Akerson, 2010).

The Lederman model separates NOS to the nature of Scientific Knowledge (NOSK) aspects and the nature of Scientific Inquiry (NOSI) ones (Lederman, 2019). The NOSK aspects are shown in Table 1.

Table 1. NOSK Aspects according to Lederman, 2019

Aspect	Description
A1	Scientific knowledge is empirical, based on our senses and extensions of them
A2	Scientific knowledge is inferential, observations and inferences are different
A3	Scientists' creativity and imagination are needed in all parts of scientific research
A4	Even though objectivity is the goal, subjectivity within scientists is inevitable, derived from scientists' personal beliefs, background knowledge, training, expectations, etc
A5	Scientific knowledge is durable but changes in the light of new evidence
A6	Scientific knowledge is culturally embedded; it affects and is affected by societal, economical, political and/or cultural characteristics of each geographical and political era
A7	Scientific Laws and Theories are different kinds of knowledge; Laws are structured mathematical relationships, whereas Theories provide a well-substantiated framework of why a phenomenon happens.

Taking these considerations into account, a program based on Lederman's model was designed to familiarize physics students with NOSK aspects and their teaching.

This model was selected because it offers a practical framework for educational contexts in which the science curriculum does not explicitly prioritize NOS. It is easier for teachers to comprehend and integrate into their teaching practices (Koumara, 2024), while also benefiting from established instruments to assess NOS knowledge, such as the VNOS-D+ questionnaire (Abd-El-Khalick, 2014).

Furthermore, given the focus of the present study on students' lesson plans, three instructional approaches for integrating NOSK were considered: History of Science (HOS), Scientific Inquiry (SI) and Socio-scientific Issues (SSI) (Koumara, 2024). Each of these approaches offers affordances and challenges for NOSK teaching, making it important for future teachers to be familiar with all of them when designing lesson plans. Examining how students select and implement these approaches provides valuable insight into their pedagogical reasoning and their understanding of NOSK integration in science teaching.

Research Questions

The present study was guided by the following research questions:

a) What views do students hold regarding aspects of the Nature of Scientific Knowledge (NOSK) prior to the instructional program, and how do these views change following the program?

b) Which teaching approaches do students adopt when designing lesson plans that aim to integrate NOSK aspects?

c) To what extent do students integrate NOSK aspects explicitly and reflectively in their lesson plans?

Together, these research questions address whether pre-service physics students are able to design effective lesson plans in which NOSK is incorporated as an explicit and reflective component of science teaching.

Methodology

The Participants And The Context

The sample of the study consisted of 64 students from the Physics Department of Aristotle University of Thessaloniki, Greece, who were in the process of obtaining their teaching certificate. As part of the coursework, they followed to obtain their teaching qualification, the students attended a 5-hour program focusing on the Nature of Scientific Knowledge (NOSK), which constitutes the focus of the present study. Thirty-one students attended the program during the academic year 2023-24 and thirty-three during the academic year 2024-25. Within this context, students participated in two interactive lectures and two workshops. The lectures focused on core aspects of NOSK and on instructional approaches for teaching NOSK through History of Science, Scientific Inquiry, and Socio-Scientific Issues. The workshops included the Signals from Space activity from Perimeter Institute and a black-box activity involving electric circuits (Koumara, Plakitsi & Lederman, 2022). Participants were provided with presentation files of the program and relevant articles on NOSK and its teaching. As part of the course requirements, students were asked to design and submit a 2000-word lesson plan that emphasised the explicit and reflective integration of NOSK aspects.

Data Collection And Analysis

Multiple sources of data were collected and analysed to address the research questions of the study. Prior to the beginning of the program, all participants completed the VNOS-D+ questionnaire within approximately 40 minutes. The questionnaire provided insights into students' initial views on aspects of the Nature of Scientific Knowledge (NOSK) and served as a pre-test.

Following the completion of the instructional activities of the program, students were given approximately one month to develop and submit a 2000-word lesson plan, which served as a post-test. Students were asked to design the lesson plan by explicitly and reflectively incorporating as many NOSK aspects as possible, providing insights into their newly acquired knowledge. They

were free to select any topic from subjects taught in Greek Secondary Education that a science teacher may be assigned to (Physics, Chemistry, Biology, Geography). Each lesson plan was examined with regard to (a) the NOSK aspects addressed and (b) the extent to which these aspects were integrated explicitly and reflectively. In addition, students were asked to complete a table at the end of their lesson plan, describing how each NOSK aspect had been incorporated. This information was analysed in conjunction with the lesson plan content in order to assess students' understanding of each NOSK aspect.

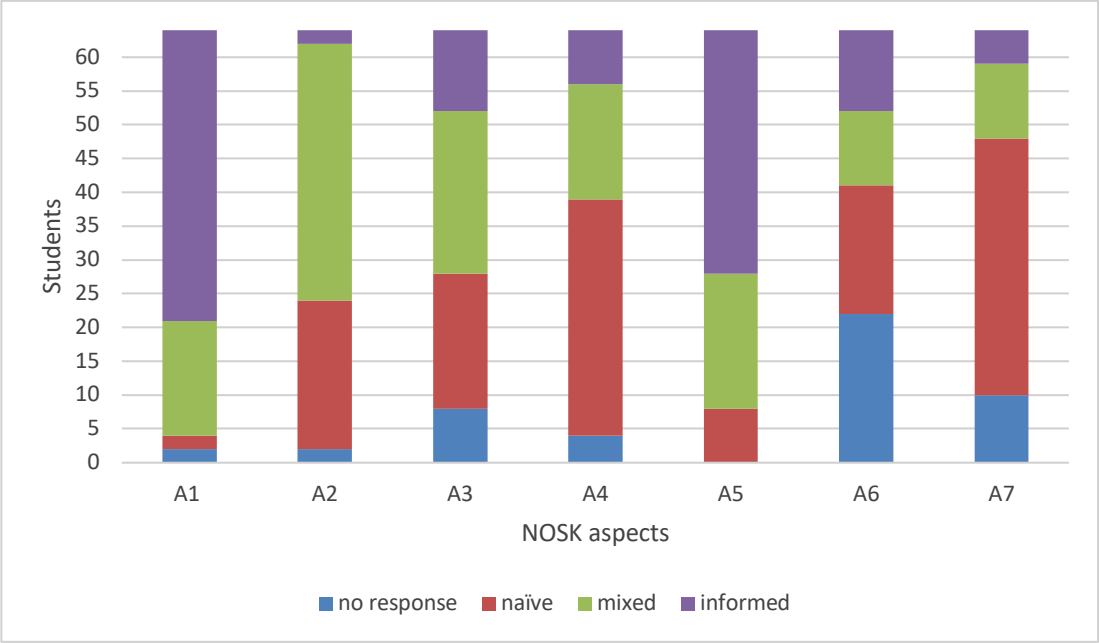
Additionally, semi-structured interviews were conducted with five students who responded to an open call at the end of the whole process. The interviews provided further insights into students' understanding of NOSK and their confidence in designing lesson plans that incorporate NOSK aspects.

Results and Discussion

Students' NOSK Views Before And After The Program

Analysis of students' VNOS-D+ responses before the program indicated distinct patterns in their views on the NOSK aspects. Students' responses were categorized into four levels (no response, naïve view, mixed view, and informed view). The distribution of students' views across the NOSK aspects is presented in Figure 1.

Figure 1. Results from the VNOS-D+ questionnaire before the beginning of the program.

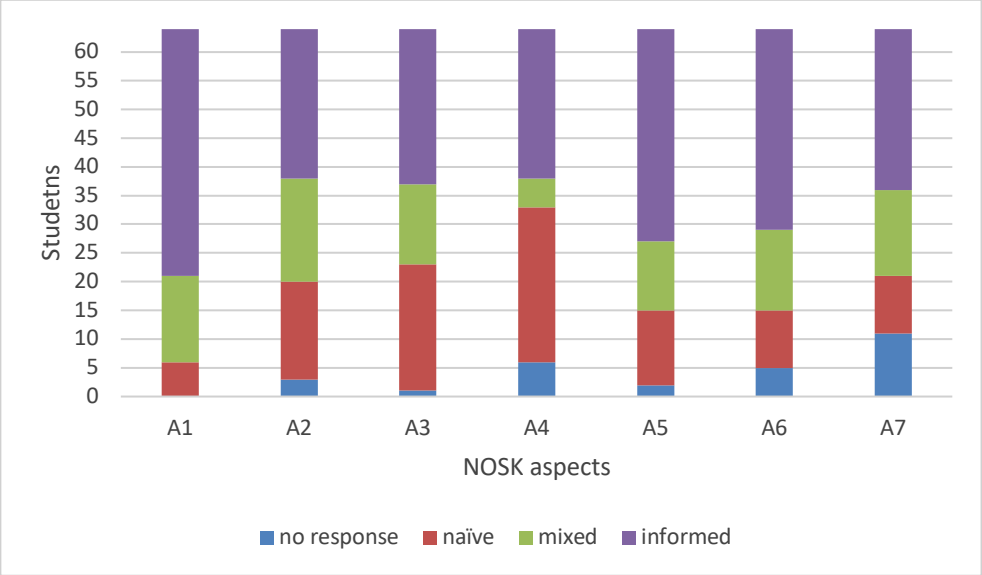


As shown in Figure 1, students demonstrated relatively high levels of awareness of the empirical (A1) and tentative (A5) aspects of NOSK, whereas limited awareness was observed for the subjective aspect (A4) and for the distinction between scientific theories and laws (A7). Mixed views were prevalent regarding the differences between observations and inferences (A2) and the creative aspect of science (A3). Concerning the A2 aspect, most students mentioned that "models illustrate scientific evidence", but their explanations often revealed limited understanding of how models support the interpretation of evidence, as reflected in statements such as "scientists insert data into a specific model and interpret the evidence taken out". Regarding creativity, all students acknowledged its role in the design of new experiments, but half of them did not refer to its presence during data collection and analysis. Twenty students claimed that creativity, in the form of ingenuity, is involved in all stages of scientific research, with twelve of them providing elaborated explanations, like "*Creativity appears at every stage of scientific research, especially when a scientist gets stuck and has to think of new ways to use the available data. Through the*

scientist's inventiveness and insight, scientific knowledge expands». Many students (22/64) did not respond to items related to the culturally embedded aspect of science (A6). Among those who did respond, naïve views were dominant: ten students focused primarily on ethical dilemmas faced by scientists, while ten others emphasized scientists' interactions with the social and cultural context in which they live.

Following the completion of the program, students' understanding of NOSK aspects, inferred from the analysis of their lesson plans and compared with their initial views, is presented in Figure 2.

Figure 2. Post-test NOSK aspects understanding, inferred from the lesson plans.



As shown in Figure 2, students' understanding improved across all NOSK aspects after the completion of the program. High levels of informed views (A1 and A5) were maintained, with fewer naïve answers. Evidence of improved understanding was also observed for the difference between observations and inferences (A2), which was articulated in approximately half of the lesson plans through the consistent use of appropriate verbs. Similarly, twenty-eight students were able to correctly describe the distinction between scientific theories and laws (A7). The creativity (A3) and objectivity (A4) aspects were clearly developed. Regarding the creativity aspect, students who described it correctly connected it with the role of critical experiments and the use of alternative models in data interpretation. Objectivity was frequently discussed as a collective and temporal achievement: students described how an initially tentative explanation becomes established as scientific knowledge through repeated observations and the contributions of multiple scientists over time. Finally, regarding the culturally embedded aspect (A6), thirty-five students linked scientific knowledge to the social and historical conditions of different eras, referring, for example, to the impact of the Catholic Church on Galileo's work, which did not apply during Newton's era.

Teaching Approaches Used In Students' Lesson Plans

Students employed different teaching approaches to integrate NOSK aspects in their lesson plans. Specifically, NOSK was addressed through approaches drawing on the History of Science (HOS), Scientific Inquiry (SI), Socio-scientific Issues (SSI), or combinations of these approaches. The distribution of teaching approaches across the 64 lesson plans is presented in Table 2.

As shown in Table 2, most students used a combination of Scientific Inquiry and History of Science. In these lesson plans, students combined historical narratives describing the development of scientific concepts (usually through YouTube videos) with inquiry-based

activities, such as simulations or laboratory experiments related to the phenomenon under study. Lesson plans based exclusively on the History of Science approach relied exclusively on historical narratives, whereas those adopting a Scientific Inquiry approach focused mainly on experimental or simulation-based activities.

Table 2. Teaching approaches used in the lesson plans.

Teaching approach	Number of lesson plans
History of Science	6
Scientific Inquiry	22
Socio-scientific Issues	3
History of Science/Scientific Inquiry	28
All three combined	1
Completely traditional lesson plan	4

Lesson plans adopting a Socio-scientific Issues (SSI) approach were relatively limited in number. Specifically, three lesson plans addressed NOSK aspects through SSI: one focused on electric circuits and two on climate-related topics taught in Geography. In addition, one lesson plan combined all three teaching approaches (History of Science, Scientific Inquiry, and Socio-scientific Issues) and was developed in the context of a biology lesson on respiration taught in the 10th grade.

Table 3. Duration of teaching periods in the lesson plans.

Teaching periods	Number of lesson plans	Teaching periods	Number of lesson plans
1	8	6	1
2	38	7	0
3	9	8	1
4	6	9	0
5	0	10	1

The average duration of students' lesson plans was 2.48 teaching periods, as shown in Table 3. Thirty-eight students (more than half) developed lesson plans with a duration of two teaching periods, which constituted the most common choice. Lesson plans lasting three teaching periods were proposed by nine students, while a single teaching period lesson plan was designed by eight students. Two students suggested a whole project through their lesson plans, with durations of eight and ten teaching periods. Overall, the distribution of lesson plan duration indicates that all students, apart from eight, recognized the need for extended instructional time to support discussion and the organization of learning activities when integrating NOSK aspects. At the same time, the presence of lesson plans designed for a single teaching period highlights the practical difficulty of addressing both scientific content and NOSK within limited instructional time.

The topics addressed in the students' lesson plans are presented in Table 4. The distribution shows that certain topics were selected more frequently, such as free fall and horizontal throw, whereas

other topics appeared only once across the lesson plans, including the photoelectric effect, respiration, and heat transfer.

Adequacy Of Students' Lesson Plans With Respect To NOSK

At the end of the lesson plan, students completed a table indicating which NOSK aspects they had addressed and how these aspects were integrated into their instructional design. Analysis of the lesson plans showed varying levels of adequacy in the integration of NOSK aspects. Based on predefined criteria, lesson plans were classified into three categories: (a) sufficient lesson plans, which integrated multiple NOSK aspects in informed ways through explicit and reflective instructional approaches; (b) partially sufficient lesson plans, in which NOSK aspects were present but addressed implicitly or inconsistently; and (c) insufficient lesson plans, in which NOSK aspects were largely absent.

Table 4. Topics from lesson plans.

Topics	Times used in lesson plans
Free fall	8
Horizontal Throw	6
Newton's Laws Electric Circuits Electric forces Work/Mechanical Energy	5
Buoyancy Light Atomic models	3
Earthquakes and volcanoes Oscillations Solutions – stoichiometry The climate of Greece Circular motion	2
Photoelectric effect Centripetal force Respiration Momentum Waves Heat transfer	1

Seventeen lesson plans (27%) were classified as sufficient. These lesson plans demonstrated informed views of NOSK aspects and incorporated them explicitly throughout the instructional activities. In these lesson plans, NOSK was discussed in detail through the proposed activities. These lesson plans reflected an understanding that addressing NOSK aspects requires extended discussion, with explicit emphasis on each aspect and opportunities for students to articulate and reflect on their ideas. Ten of these lesson plans explicitly stated NOSK objectives at the beginning of the instructional design. Regarding instructional approaches, eight of the seventeen sufficient

lesson plans combined History of Science and Scientific Inquiry, seven used only the Scientific Inquiry approach, and two used only the History of Science. Lesson plans that incorporated Socio-scientific Issues were limited in number and did not fall within this category. Across these lesson plans, the historical narrative was used to introduce all NOSK aspects.

NOSK aspects in sufficient lesson plans were integrated through examples, both in HOS and SI, especially for the creative (A3) and the culturally embedded (A6) aspects, by asking students to finish a story using their current knowledge, by constructing a mind-map of the evolution of scientific knowledge, by introducing the tentative aspect (A5), or by describing a critical experiment, and reflecting on it to highlight creativity (A3). Creativity was also addressed through tasks in which students were asked to design an experiment. The distinction between observations and inferences (A2) was discussed with the use of proper verbs, such as observe, see, feel, note for the first, and infer, conclude, assume for the second. The distinction between theories and laws was also discussed when present (A7).

Twenty lesson plans (42%) were classified as partially sufficient. In these cases, students integrated NOSK aspects implicitly, and they only referred to NOSK in the summary table. While some of these lesson plans reflected an understanding of NOSK aspects, others revealed difficulties in effectively incorporating them into teaching. The NOSK aspects most frequently found to be challenging in these lesson plans were the distinction between observation and inferences (A2), the objective aspect (A4), and the difference between theories and laws (A7)

Finally, twenty lesson plans (31%) were classified as insufficient with respect to NOSK integration. These lesson plans followed traditional science teaching approaches, with NOSK aspects absent even at an implicit level. Four lesson plans contained only lecturing on scientific knowledge.

Insights From Student Interviews

Semi-structured interviews were conducted with five students to further explore their views on NOSK and their experiences with designing NOSK-oriented lesson plans. Interview data provided additional qualitative insights that complemented the findings from the written lesson plans. All students reported that they had not heard of NOSK before the program, neither as a concept nor the aspects, in an organized manner. However, they had heard some aspects, mainly the empirical (A1) and the tentative (A5), and they had assumed the others. One referred to a prior discussion of the relationship between science and society (A6) during secondary education, which had taken place in the context of a language course rather than a science class. Overall, students described recognizing elements of NOSK retrospectively in their school and university experiences and reported that the explicit presentation of NOSK aspects during the program facilitated their understanding.

Interviewed students emphasized the significance of NOSK for enhancing students' understanding of science and fostering scientific literacy. At the same time, three students expressed uncertainty regarding the extent to which in-service science teachers are familiar with NOSK aspects and how to teach them. These students highlighted the need for further professional development opportunities related to NOSK teaching.

Regarding the design of the lesson plan, all interviewees described the task as initially challenging. However, once they had selected a topic and started working on it, they reported gaining clarity on how to proceed. Students noted that the instructional resources provided during the program supported their work, and three students additionally reported seeking out and studying further NOSK-related literature independently.

Discussion

The present study focuses on students' understanding of the Nature of Scientific Knowledge (NOSK), the teaching approaches they adopted when designing lesson plans, and the adequacy of NOSK integration in these plans, after participating in a short training intervention (5-hour program) on NOSK. The findings indicate that, despite a mainly traditional and content-focused curriculum, physics students were able to identify multiple opportunities for integrating NOSK across a range of topics. The development of seventeen (27% in total) sufficient lesson plans further suggests that even short instructional interventions can support students in adopting more explicit and reflective approaches to NOSK teaching.

Regarding the first research question, which concerned students' understanding of NOSK aspects before and after the program, the findings indicate substantial improvement across all NOSK aspects. Students initially demonstrated limited or mixed views on several aspects, particularly those related to subjectivity, the distinction between theories and laws, and the culturally embedded aspect, while they are familiar with the empirical and the tentative aspects. The school curriculum helps students use these two aspects in examples of scientific observations and in narratives of how scientific knowledge evolves. These findings are in line with previous research (Koumara & Plakitsi, 2020). The analysis after the completion of the program revealed more informed and coherent understandings, as reflected in the lesson plans.

With respect to the second research question, which examined the teaching approaches students employed to address NOSK, results show a strong preference for combining History of Science and Scientific Inquiry. This pattern suggests that students perceive these approaches as complementary resources for supporting explicit discussions of NOSK, while approaches based exclusively on Socio-scientific Issues were less frequently adopted.

Finally, regarding the third research question, which focused on the adequacy and explicitness of NOSK integration in students' lesson plans, the findings reveal a mixed picture. Although a notable proportion of lesson plans demonstrated informed, explicit, and reflective integration of NOSK, a considerable number remained implicit or insufficient, pointing to ongoing challenges in translating NOSK understanding into coherent instructional practice. This pattern indicates that some students may not have fully engaged with the provided resources, as reflected in their limited understanding of the NOSK aspects.

Limitations Of The Study

The findings cannot be generalized to all physics students in other institutions, as the participants were drawn exclusively from one university department and reflect the specific curriculum followed by students pursuing a teaching certificate. Moreover, obtaining a teaching certificate is not mandatory in Greece, and some future science teachers may acquire pedagogical qualifications through postgraduate studies, which may involve different forms of preparation.

The instructional program was short-term, so a deeper and more sustained understanding is likely to require longer-term engagement, including repeated opportunities to teach NOSK in authentic classroom settings.

Lastly, even though students received feedback on their lesson plans, they were not required to revise or resubmit their work. This means that some students might have enhanced their understanding of NOSK.

Conclusion

This study examined physics students' understanding of the aspects of the Nature of Scientific Knowledge (NOSK) and their ability to integrate these aspects into lesson planning following a

short, focused instructional program. The findings indicate that, although students initially held mostly mixed views on several NOSK aspects, targeted instruction can support meaningful development in both NOSK understanding and instructional application. A notable proportion of students were able to design lesson plans that explicitly and reflectively integrated NOSK aspects within the existing secondary science curriculum. This outcome suggests that even short-term interventions can enable pre-service teachers to move beyond content-focused instruction and to consider NOSK as an integral component of science teaching. Further engagement with NOSK is needed before these students can integrate NOSK into their classrooms when they become regular teachers.

Future Work

Future research could build on the present findings by examining the effects of sustained and iterative NOSK-focused instruction embedded within undergraduate science teacher education programs. In parallel, extending NOSK-focused professional development to in-service teachers would provide insight into how teaching experience shapes NOSK integration in contexts where NOSK is not explicitly emphasized in the curriculum. Comparative studies involving pre-service and in-service teachers could further elucidate the role of classroom experience in shaping both NOSK understanding and its instructional enactment. Finally, comparative investigations of instructional approaches, such as History of Science, Scientific Inquiry, and Socio-scientific Issues, could clarify their respective affordances for supporting sustainable NOSK integration across scientific domains and educational levels.

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Primary Teachers' Competencies And Difficulties In Teaching Measurement Uncertainty: Pedagogical Challenges Related To Nature Of Science

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This paper investigates the primary teachers' ability to explicitly address scientific practices and particularly the nature of measurement into their experimental teaching scenarios after their participation in a related STEM Education Master's degree course. The content of the course attended by the primary teachers was based on "Guide to the expression of Uncertainty in Measurement", adapted to primary teachers' level and needs. Primary teachers' teaching scenarios were qualitatively analysed to examine whether and to what extent they have addressed aspects of measurement practices. Preliminary findings show that although primary teachers can design experimental activities for their students, setting explicit learning goals related to measurement procedures, they focus on limited aspects of scientific measurement, such as the causes of measurement uncertainty. They do not frequently mention aspects such as the use of statistical tools, the significance of measurement spread and the need for repetitions of measurements. Preliminary findings provide evidence for further research on how difficulties in teaching measurement concepts are related to difficulties in understanding Nature of Science, and particularly aspects related to observation, evidence, inference, laws and theories.

Keywords: Nature of Science, Measurement

Introduction

Measurement has a long history, stretching back at least two and a half thousand years across a multitude of cultures. Teaching about measurement is closely related to teaching about science, since natural sciences are very connected to measurement procedures. The concept of measurement uncertainty includes key concepts of the scientific method: random and systematic error, calibration, hypothesis testing, experimental design, modelling, approximation, etc. It can be considered as one of "threshold concepts" in science teaching, as it is important for students to identify different sources of uncertainty, quantify results, and take these results into account when planning experiments, analysing data and drawing logical conclusions.

Understanding scientific measurement has been recognized for a long time as an important part of science education by policy bodies (AAPT, 1998; OECD, 2023). Teaching and learning about scientific measurement are an essential aspect of scientific literacy (Osborne et al., 2003). The IPCC 6th Assessment Report (2023) for citizens is indicative of how scientists communicate results to non-scientists. Citizens must be fluent in the concept of measurement and uncertainty in order to be able to read, understand and interpret results in order to inform decisions. This way, uncertainty increases, and does not decrease, confidence in science.

Nature of measurement is also related to scientific and engineering practices, in the context of Next Generation Science Standards (NGSS Lead States, 2013). Particularly, NGSS addresses both measuring processes: (1) collect data (determining the size, materials, precision, etc), and (2) process the data, as depicted in the scientific practices. According to NGSS, during planning and carrying out investigations, students should be able to produce data to serve as the basis for evidence: decide on types, quantity, and accuracy of data needed to produce reliable measurements and consider limitations on the precision of the data. Moreover, regarding using mathematics and computational thinking, students are expected to measure, estimate, and/or

graph quantities such as area, volume, weight, and time to address scientific and engineering questions and problems. Greek primary science education curricula also include learning goals relative to measurement procedures. Students are introduced to the measurement of various quantities, from measuring length, mass, area, volume, duration, and temperature to calibrating thermometers under teacher guidance. At this point, it can be noted that both international and national programs are ambitious about measurement skills in primary education.

Despite the importance of teaching and learning measurement procedures, few studies have dealt with young children's reasoning about measurement and teachers' competencies in responding to difficulties. Regarding primary students' difficulties in measurement, they are focused on the concept of uncertainty. The realization of data incorporates an inherent uncertainty leading to imperfect measurements, confuses students who take science's clarity and certainty for granted. During experimental procedures students expect "a unique right answer" to any measurement. For them, a scientifically correct measurement is the one that is not accompanied by any uncertainty (Allie et al., 2003). Students do not separate the terms error and uncertainty. They use the terms interchangeably, as they attribute to "human error" any of the unexpected results (Allie et al., 2003). The work of Buffler et al (2009) has revealed a strong relationship between measurement uncertainty understanding and students' views on Nature of Science (NoS).

Regarding undergraduate science students, although they are very skilful in carrying out experiments and data analysis, they seem to have difficulties in realizing the reasons for such processes (Buffler et al., 2001). Particularly, science students have difficulty in distinguishing accuracy and precision, and they consider the first data as "prominent" and the following as "confirmatory" (Majiet & Allie, 2019). Regarding primary teachers, very limited research is available, revealing teachers' inability to articulate their knowledge of concepts and processes related to measurement (O'Keefe & Bobis, 2008). Georgaki & Stefanidou (2023) found that although most teacher students recognize scientific measuring as an important part of the scientific process, they had several difficulties regarding the concept of uncertainty, such as not distinguishing between uncertainty in the kitchen and uncertainty in the laboratory, attributing uncertainty in systematic errors and inability to conceptualize random errors as part of the measurement precision. The above-mentioned research findings gave rise to this research, which investigates if and to what extent primary teachers can address measurement concepts in their experimental teaching scenarios, and particularly what the arising difficulties are.

Methodology

Research Questions

According to the work of Munier et al (2013), the research questions are as follows: What difficulties do primary teachers face when designing experimental teaching scenarios including learning goals and teaching activities regarding:

1. Causes of uncertainty (quantity, instrument, and the experimenter)?
2. Statistical tools such as frequency tables and bar charts to represent data and results?
3. Need for multiple measurements

Sample – Place – Time

The research took place during the academic year 2024-2025, in the Department of Pedagogy and Primary Education, of the National and Kapodistrian University of Athens. The sample was a convenience sample and consisted of 30 primary teachers, who attended a Master's Degree program on STEM Education, and particularly a course on Measurements and Sensors.

The Educational Framework

All participants attended the course Measurements and Sensors, which included 10 three-hour laboratory meetings in person. The course had two main parts: The first half (five laboratory meetings) aimed at introducing graduate students in measurements and uncertainty. The content was based on the work of Buffler et al (2008), tailored for primary teachers, in the context of GUM approach. Primary teachers (graduate students) familiarized themselves with the concepts of measurand and units of measurement, producing data of length, mass, volume, time, temperature, voltage and current. Participants were introduced to the concept of uncertainty of measurement and the difference between uncertainty in "everyday" measurements and "scientific" measurements. During the process, they familiarized themselves with basic elements of measurement theory, such as the classification of errors as systematic and random, they participated in certain activities on precision and accuracy and worked on the need for repetitions of measurements. Finally, students, through simple examples, were introduced to the concept of error propagation.

Data Collection And Analysis

Participants in the present study were asked to produce a two-hour experimental teaching scenario on a topic of their choice for primary school, and especially grades K-5 and K-6. The main sources of data were participants' teaching scenarios and field notes.

Data were analysed according to the qualitative content analysis method (Mayring, 2015). For reliability reasons, all data were independently analysed by the two authors, to debate possible differences and reach a final classification. Both teaching goals and teaching activities were analysed regarding: 1. The identification of causes of uncertainties 2. The use of statistical tools and 3. The need for repeatability.

Findings

The first findings reveal that primary teachers, graduate students of a Master's degree program in STEM education, are able to design experimental teaching scenarios focusing on the concept of measurement uncertainty. Analysis of their teaching scenarios reveals that although they all have learning goals related to measurement procedures, not all aspects are equally represented.

Particularly, regarding the first research question (causes of uncertainty related to quantity, measuring instrument and the experimenter), the analysis showed that the majority of the teaching scenarios (20 out of 30) included both learning goals and corresponding activities addressing this issue. Teachers tended to introduce the distinction between systematic and random errors explicitly, indicating an awareness of different sources of measurement uncertainty. However, in many cases, the identification of errors was implicit rather than formally defined, often embedded within given examples or classroom discussions. Additionally, teachers frequently encouraged students to record and reflect on variables that could influence measurements, such as light conditions or distance, typically through guiding questions like "Why do measurements differ?". This suggests that while teachers recognized and addressed factors contributing to uncertainty, these were often approached in a contextual and exploratory manner rather than through formalized conceptual frameworks.

With respect to the second research question (use of statistical tools), only a limited number of teaching scenarios (10 out of 30) included explicit learning goals and activities related to data representation and analysis. When statistical tools were addressed, teachers mainly focused on designing and/or explaining simple graphical representations, such as temperature–time graphs, or on interpreting ready-made diagrams and bar charts by asking students to provide explanations

of the displayed results. In addition, some scenarios included basic calculations of averages. However, teachers' engagement with statistical thinking remained limited, as more advanced concepts, such as the importance of the spread or variability of measurements, were entirely absent from the teaching scenarios. Overall, statistical tools were approached in a procedural manner, emphasizing representation and calculation rather than deeper reasoning about data.

Concerning the third research question (the need for multiple measurements), fewer than half of the teaching scenarios (12 out of 30) explicitly emphasized the importance of repetition. In these scenarios, teachers typically supported repeated measurements by providing pre-structured data tables for students to complete and by encouraging comparisons between different groups' data sets. Some activities also prompted students to reflect on the reasons for conducting multiple measurements. Nevertheless, repetition was mainly treated in a mechanical way, focusing on the act of repeating measurements rather than on its epistemic role. Links between repeated measurements and key concepts such as reliability or precision of results were largely absent, and only limited emphasis was placed on the significance of measurement spread. This indicates that, although repetition was operationally included, its conceptual importance in experimental inquiry was not sufficiently developed.

Implications For Nature Of Science Teaching

The difficulties identified in teaching measurement concepts have important implications for the teaching of the Nature of Science (NoS). Measurement uncertainty can foster essential habits of mind for scientific reasoning and citizenship in a world shaped by science and technology. Shifting the focus from "error" to uncertainty can help students move away from a rigid right–wrong view of science and toward an understanding of scientific knowledge as tentative, evidence-based, and open to revision. By grappling with uncertainty, students are more likely to appreciate experimentation as a process of inquiry rather than a procedural search for correct answers, and to interpret data not as absolute truths but as results associated with a range of confidence. This perspective mirrors authentic scientific practice, where scientists rarely obtain a single "true" value but instead report results in terms of precision, accuracy, and confidence intervals. Moreover, challenges in teaching measurement uncertainty are closely linked to broader NoS dimensions, including observation, evidence, inference, the relationship between laws and theories, and the objectivity and subjectivity of measurement processes, as well as the intersubjective nature of scientific results (Stefanidou & Skordoulis, 2014; Mari et al., 2017; Stump et al., 2024). Explicit attention to distinctions such as accuracy versus precision can therefore support a more coherent integration of measurement concepts and NoS, enhancing students' understanding of how scientific knowledge is constructed.

Conclusions

Overall, the findings indicate that primary teachers face substantial difficulties when designing experimental teaching scenarios that meaningfully address measurement uncertainty. Although some aspects of uncertainty are acknowledged, teachers' approaches largely remain at the level of broad or implicit discussion, without a clear conceptual distinction between error and inherent uncertainty. The limited use of statistical tools further suggests a lack of familiarity with integrating basic statistical reasoning into experimental teaching, restricting students' opportunities to interpret data beyond simple representations or averages. Similarly, while the need for repeated measurements is occasionally emphasized, it is often treated mechanically without adequately highlighting its role in reducing uncertainty or improving the reliability and precision of results. Taken together, these findings reveal that key dimensions of experimental reasoning—such as variability, confidence in measurements, and the epistemic status of data—are insufficiently addressed, pointing to a fragmented understanding of measurement uncertainty

in primary science teaching.

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The Growing Need For STEM Careers And The Potential Pathways For Independent Scientists

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The growing demand for STEM professionals highlights the need to explore alternative career pathways for scientists beyond traditional academia and industry. Despite efforts to encourage STEM career persistence, issues such as limited academic positions hinder long-term engagement in scientific fields. The mismatch between PhD holders and private sector employees further exacerbates this challenge, necessitating new opportunities for independent researchers.

This study investigates the potential of non-profit organizations as viable career alternatives for STEM professionals in Japan by analysing research funding trends. Using data from the KAKEN database, we examine the research achievements of non-profit research institutions, such as general incorporated associations (GIA), non-profit organizations (NPO), and social welfare corporations (SWC). Our findings revealed that independent researchers within these organisations' secure competitive grants, with notable participation in early career and small-scale research funding schemes.

Case studies highlight two key patterns: organisations that collaborate with universities to support early career researchers, and those that sustain long-term, independent scientific enquiry. While some organisations provide transitional opportunities for post-doctoral researchers, others enable senior scientists to continue their work beyond academia. Despite financial and institutional barriers, these alternative research pathways contribute to scientific progress and expand STEM career possibilities.

This study underscores the importance of recognising and supporting independent research outside conventional institutions. Future research should involve qualitative interviews to explore the professional development of independent scientists. By addressing funding challenges, we can foster a more inclusive and sustainable STEM workforce that ensures diverse contributions to scientific innovation.

Keywords: Independent Researcher, Academic Career, Scientist

Introduction

STEM Career And Becoming Scientists

The increasing global demand for STEM (Science, Technology, Engineering and Mathematics) professionals contrasts with a decline in student interest in STEM careers, a phenomenon known as the 'leaky pipeline.' Factors such as school experiences, parental influence, economic background, and gender shape students' motivation (DeWitt & Archer, 2015; Zhai & Liu, 2024). Despite their academic abilities, many students lose interest as they advance their education (Chen et al., 2024).

At the doctoral level, the oversupply of STEM graduates leads to employment challenges. A report by Japan's Ministry of Education, Culture, Sports, Science and Technology (MEXT, 2023) shows that only 15.8% of PhD holders secure university faculty positions, with 9.4% working as post-doctoral researchers. Many PhD graduates struggle to transition into industry because of a mismatch between their skills and corporate needs (Miki, 2019). While academia remains a primary aspiration, the reality of limited faculty positions has driven interest in alternative career pathways, including independent research.

Rise Of Scientists Outside University

There is growing attention and support for citizen scientists. ‘Citizen science’ indicates research activities conducted by non-professionals in science. (Silvertown 2009, Lusse et al. 2022). This can be performed independently by citizens or collaboration with professional scientists. In Japan, there is a framework for amateur scientists (Kimura 2021). An amateur scientist is a non-professional researcher with expertise in a specific scientific field, such as entomology, at a level comparable to or exceeding that of professional scientists in the same discipline. Here, ‘non-professional’ denotes individuals who do not rely on this activity as their primary source of income. The National Coalition of Independent Scholars defines independent scholars as individuals engaged in research without a tenure-track position or permanent university contract established in 1989. There are communities of independent researchers, such as the Japan Scientists’ Association (JSA), established in 1965. These organisations have their own peer-reviewed journals and face challenges in sustaining their activities due to limited research funds. I It is not appropriate to categorise independent scientists into citizen science or amateur science as are capable of drafting their own academic papers.

Therefore, this study focuses specifically on the funding challenges for independent scientists in Japan. Funding is one of the key factors impacting the the sustainable development of these so-called non-professionals. Exploring their funding achievement, makes it possible to discuss pursuing STEM careers as ‘scientists’ outside academia or industry. The research question in this study is as follows: Can non-profit organisations be an alternative career path for STEM professionals from the perspective of acquiring funding?

Japanese Research Grants

This study examines the Grants-in-Aid for Scientific Research (Kakenhi) funded by the Japanese government through the Ministry of Education, Culture, Sports, Science, and Technology (MEXT) and the Japan Society for the Promotion of Science (JSPS). Only researchers affiliated with recognised institutions are eligible to apply for these grants. These research organisations should fulfil the listed criteria, such as ‘At least 1/5 of the researchers who are currently affiliated with the applicant institution at the time of application have published an original paper in a journal or similar publication within the past year’, and ‘The per capita research expenditure of the applicant organisation as a whole, excluding external funds (the amount for the previous year of the application), must be at least 360,000 yen per year’ (MEXT 2021). This requirement ensures that researchers have completed seminars on research ethics and integrity and grants are used properly.

According to the list of research organisations of KAKEN (JSPS 2022), there are five main categories of research organisations in Japan: 1) universities, 2) colleges and technical colleges, 3) inter-university research institutions and foundations, 4) independent administrative institutions, and 5) others. In this paper, we discuss those organisations in the last group. By doing so. we can determine what kind of research is being conducted in such organisations and what challenges exist. This would ensure the diversity of places where researchers can become active in society.

Methods

Sample And Data Collection

The KAKEN database (NII 2023) was used for analysis, covering 1,043,559 research projects from 1964 to 2024. The list of research organisations (JSPS 2022) was collected in January 2024. Based on this list, organisations were categorised using a numbering system. In total, 2059 organisations are listed in the list. Serial numbers were assigned to each organisation.

Organisation numbers starting with 1, 2, and 3 were universities (N=825); those starting with 4, 5, and 6 were colleges (N=313), technical colleges (N=58), and inter-university institutions (N=16), respectively; and those starting with 7, 8, and 9 were others (N=845). 'Others' included foundation organisations, national corporations, stock companies, medical corporations, specified non-profit-making corporations, welfare corporations, and religious groups. To examine only the organisations needed to work as professional researchers outside of universities or companies, this study has focused on organisations that do not run for profit; therefore, general incorporated associations (GIA), non-profit organisations (NPO), and social welfare corporations (SWC) were studied.

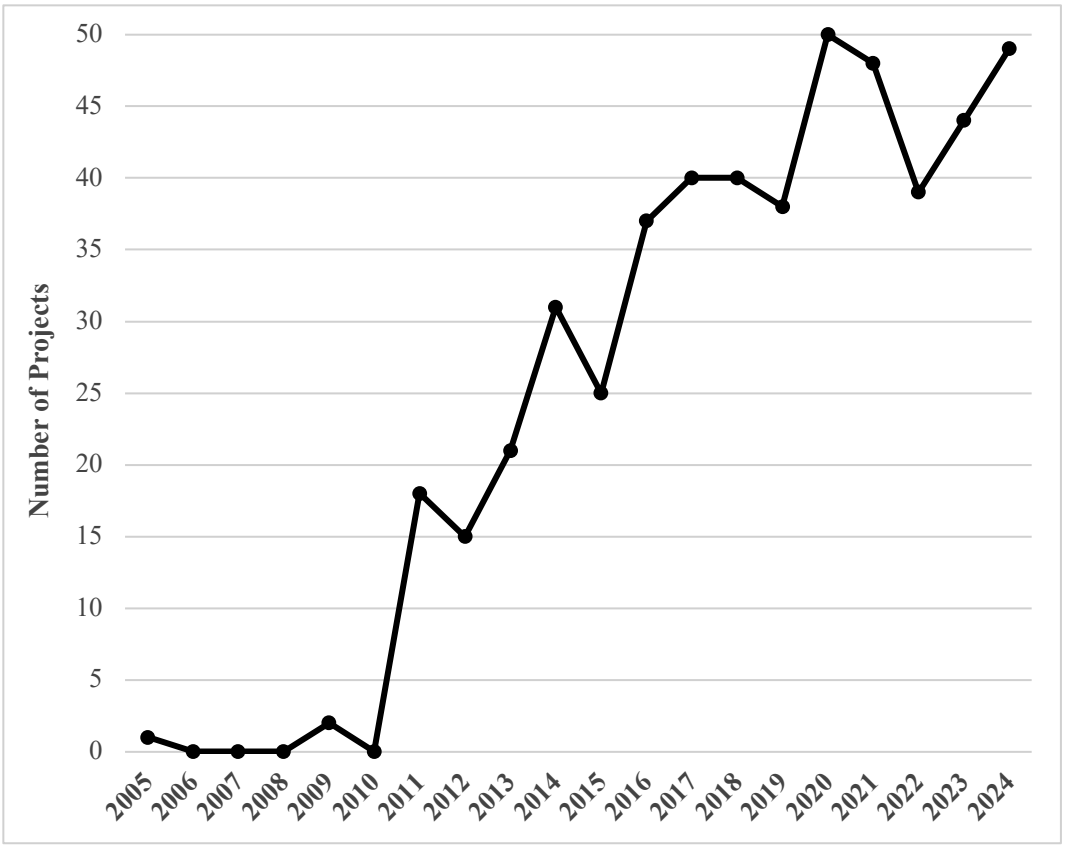
Based on the KAKEN database, we looked into the following categories for GIA, NPO and SWC; 1) Number of research projects; and 2) Budget types and actual budget.

Results

Trends In Research Funding

Figure 1 indicates that there has been a clear, rapid growth in the number of research projects accepted by Kakenhi. This growth can be explained by the National University Corporation Act, enacted in 2004. Before 2004, Japanese national universities were government agencies; afterwards, they became National University Corporations. Universities still receive funding from the government; however, the funds are decreasing annually, primarily due to the overflow of post-doctoral students. Researchers have attempted to find opportunities to conduct research outside universities.

Figure 1. Number of Research Projects.



Budget Types

There are several budget types varies its duration and total budget. Table 1 summarises current budget types. For example, Grants-in-Aid for Scientific Research (A, B, C) fund research projects by one or more researchers for three to five years, with a total budget of less than 5,000,000 JPY, between 5,000,000 JPY and 20,000,000 JPY, between 20,000,000 and 50,000,000 JPY. Grants-

in-Aid for Early-Career Scientists funds research projects run by young researchers under the age of 39 or who have been awarded a doctoral degree for less than 8 years excluding the parental leave period for two to four years. Researchers who have been awarded a doctoral degree within the past eight years are eligible for amounts up to 5,000,000 JPY for a duration of 2–5 years.

Table 1. Budget Type and Numbers.

Name	Budget
Grant-in-Aid for Transformative Research Areas	less than 5,000,000 JPY or between 5,000,000 and 30,000,000 JPY
Grant-in-Aid for Scientific Research (S)	between 50,000,000 and 200,000,000 JPY
Grant-in-Aid for Scientific Research (A)	between 20,000,000 and 50,000,000 JPY
Grant-in-Aid for Scientific Research (B)	between 5,000,000 JPY and 20,000,000 JPY
Grant-in-Aid for Scientific Research (C)	less than 5,000,000 JPY
Grant-in-Aid for Research Activity Start-up	less than 3,000,000 JPY
Grant-in-Aid for Early-Career Scientists	less than 5,000,000 JPY
Grant-in-Aid for Challenging Research (Pioneering)	between 5,000,000 JPY and 20,000,000 JPY
Grant-in-Aid for Challenging Research (Exploratory)	less than 5,000,000 JPY

On average, an organisation obtains ¥8,055,361 per research project. There was a preference for relatively small projects. The minimum budget recorded was ¥520,000; the maximum budget was ¥131,040,000. Figure 2 (next page) shows the overview of budget types. Among these budget types, Early-Career Scientists (153) and Research Activity Start-ups (13) represented grants awarded to young scholars, comprising 34% of the total number of grants. This indicates that these researchers were not necessarily in the early stages of their careers. Their research projects are evaluated worthy of funding.

Preliminary Case Study

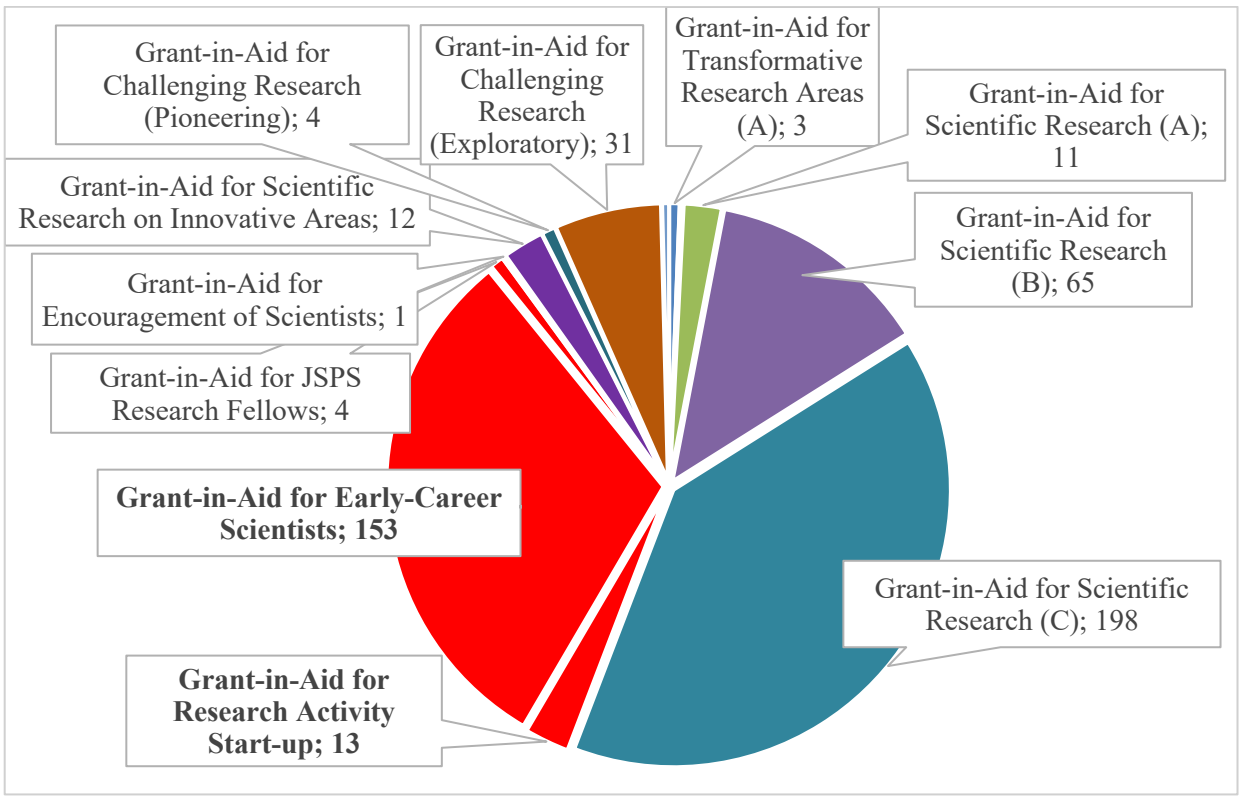
Two major organisations were analysed in depth by collecting information on webpages of organisations. There are two main patterns in how organisations conduct research projects. Some collaborate closely with universities, where principal investigators are typically university professors, and researchers stay for a short period before securing academic positions. In contrast, some organisations, particularly in natural sciences with theoretical research areas, operate independently for over five years with small teams (under ten researchers). These groups secure substantial funding and are often led by senior researchers, including retired university faculty members who continue their work outside academia.

Conclusion and Further Research

This study highlights the increasing number of independent researchers in Japan and their contributions to scientific progress. It states that researchers can work as independent professional scientists in non-profit organisations; these independent scientists are actively conducting Kakenhi-funded research. Studies on research outside universities remain limited; various researchers, including those working independently, pro bono, or as a second job, have contributed to expanding the research landscape. Thus, students' career pathways can expand, which would contribute to STEM career opportunities. Although funding opportunities exist, institutional barriers continue to pose significant challenges. Independent research can serve as a viable career path, ensuring greater flexibility and resilience in STEM professions. This research aims to demonstrate how such career paths can offer greater flexibility and resilience in STEM

professions and furthermore, raises the question: “Who are scientists, and what are the professionality of scientists?”.

Figure 2. Overview of Budget Types.



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Pre-Service Teachers' Engagement Of Scientific Reasoning: Uncovering The Mystery Of Tutankhamun's Iron Dagger

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This instrumental case study examines how pre-service teachers engage in scientific reasoning when confronted with an anomalous historical case: Tutankhamun's iron dagger. Sixty-two pre-service teachers from diverse disciplines participated in an inquiry task during the first week of a Science and Research Ethics course. Written responses were analysed using a hypothetico–deductive reasoning framework supported by a rubric-based analysis. Findings indicate that most participants demonstrated minimal or basic inquiry engagement, generating a wide range of explanations from scientifically plausible to pseudoscientific. Findings highlight the need for stronger scientific reasoning skills in teacher education to foster critical thinking and scientific literacy.

Keywords: Scientific Inquiry, Scientific Reasoning, Pre-Service Teachers

Introduction

In contemporary, media-saturated societies, individuals are increasingly required to evaluate scientific and pseudoscientific claims in everyday life. Consequently, scientific literacy extends beyond content knowledge to include the ability to reason scientifically, construct explanations, and justify claims with evidence (McNeill, 2008; Lawson, 2009). From this perspective, learning science involves engaging in the practices of science—such as generating hypotheses, evaluating evidence, and reasoning under uncertainty—rather than merely acquiring established facts. Inquiry-based science learning has been shown to support the development of scientific reasoning, increase student motivation, and promote critical thinking and problem-solving skills (Murphy et al., 2019; Taibu et al., 2021). However, research consistently indicates that both teachers and pre-service teachers often have limited opportunities to engage in authentic scientific inquiry and therefore struggle to support these practices in their future classrooms (Uyar et al., 2018). In addition, research on scientific reasoning consistently emphasizes the central role of causal and mechanistic reasoning in constructing scientific explanations. Scientific understanding requires not only identifying causes and effects but also articulating the mechanisms through which causes produce observable outcomes (Ahn & Kalish, 2000). Russ et al. (2008) argue that reasoning about mechanisms is a fundamental aspect of scientific inquiry, as mechanisms link evidence to explanation by specifying the processes underlying phenomena. Similarly, Abrams and Southerland (2001) suggest that learners often prioritize explaining why a phenomenon occurs rather than how it occurs, thereby neglecting the physical or causal mechanisms required for scientifically valid explanations.

One promising approach for eliciting and examining scientific reasoning is the use of anomalous cases—situations that conflict with established scientific or historical expectations. Anomalies create epistemic tension, prompting learners to generate hypotheses, reconsider assumptions, and evaluate evidence (Chinn & Brewer, 1993; Echevarria, 2003). Historically grounded anomalies are especially powerful because they situate scientific reasoning at the intersection of science, history, culture, and ethics, thereby supporting understanding of the nature of science (NOS) as a dynamic and human endeavour (Allchin, 2013). The discovery of an iron dagger in the tomb of the Egyptian pharaoh Tutankhamun (1332–1323 BCE) represents such an anomaly. According to conventional historical timelines, iron processing became widespread several centuries later,

making the presence of an iron artifact in this context unexpected. Explaining this finding requires reasoning under uncertainty, generating alternative hypotheses (e.g., meteoritic iron, early metalworking, trade), and evaluating their plausibility based on historical, chemical, and archaeological considerations. As such, the case provides an authentic context for examining how learners engage in scientific inquiry and hypothetico–deductive reasoning.

Although scientific inquiry has long been a central focus of science education research (Fukuda et al., 2022), relatively few studies examine how pre-service teachers' inquiry capabilities are revealed when they engage with authentic, anomalous scientific problems (Vo & Simmie, 2024). Understanding how pre-service teachers initially reason in such contexts is critical, as these epistemic practices shape how they will later design learning environments for their own students.

In the present study, the iron dagger represents an anomalous result—a finding that conflicts with established historical and scientific expectations—and therefore requires learners to reason with uncertainty, generate competing hypotheses, and judge the plausibility of explanations based on evidence. Research on students' engagement with anomalous results shows that such situations are particularly powerful for revealing how learners monitor evidence, evaluate claims, and regulate their reasoning processes, which are central components of scientific literacy (Crujeiras-Pérez & Jiménez-Aleixandre, 2017; Echevarria, 2003). Besides, historically grounded case studies, particularly those involving anomalies, are uniquely powerful for fostering students' understanding of both scientific inquiry and the nature of science (NOS) (Allchin, 2011). In the Tutankhamun task, pre-service teachers are required to argue for or against explanations (e.g., meteoritic iron, early metallurgy, pseudoscientific claims) using historical, chemical, and archaeological reasoning. Thus, the case operationalizes the broader goal of scientific literacy by making visible how participants reason, justify conclusions, and distinguish scientific explanations from speculative or non-scientific ones—precisely the competencies that science education aims to develop.

Research Question

How do pre-service teachers use scientific reasoning to generate, evaluate, and justify explanations for anomalies in historical scientific findings?

Methods

Research Design

This study was designed as an instrumental qualitative case study (Stake, 1995) examining how pre-service teachers engage in scientific reasoning when confronted with an anomalous historical scientific case. Case study methodology is particularly appropriate when the aim is to investigate complex cognitive and epistemic processes within a bounded context (Yin, 2018). The case of *Tutankhamun's iron dagger* was selected because it represents a historically authentic anomaly that requires hypothesis generation, evidence evaluation, and mechanistic reasoning, making it a powerful context for examining scientific inquiry practices.

Consistent with recommendations for qualitative case studies in education, multiple analytic strategies were employed, including rubric-based scoring and qualitative interpretation, to provide a rich and systematic account of participants' reasoning (Merriam & Tisdell, 2016). The case thus serves as an analytic lens for understanding broader challenges in pre-service teachers' engagement with scientific inquiry and hypothetico–deductive reasoning.

Context And Participants

The study was conducted as part of the Science and Research Ethics course, a compulsory general culture course offered at a faculty of education in Türkiye. The course enrolled 62 pre-service

teachers from diverse departments, including preschool education, social studies, music education, science education, and biology education, representing all four undergraduate grade levels (1st–4th year). Purposeful inclusion of participants from different disciplinary backgrounds was intended to capture a broad range of prior scientific knowledge and epistemic orientations, an approach commonly adopted in studies examining inquiry reasoning across heterogeneous teacher populations (e.g. Windschitl et al., 2012).

Data were collected during the first week of the semester, prior to formal instruction, in order to assess participants' readiness and baseline inquiry reasoning. Early-course data collection is recommended when the aim is to examine pre-existing epistemic resources rather than instructional outcomes (Hammer & Elby, 2002).

Instructional Task: A Scientific Mystery: Tutankhamun's Iron Dagger

Participants were presented with a historically grounded anomalous case titled "A Scientific Mystery: Tutankhamun's Iron Dagger." The case described the discovery of an iron dagger in the tomb of Tutankhamun (1332–1323 BCE), an artifact that contradicts established historical timelines for iron metallurgy. The case was deliberately framed as an anomaly, defined as evidence that conflicts with existing theoretical or historical expectations and therefore prompts epistemic tension (Chinn & Brewer, 1993; Echevarria, 2003). The open-ended guiding questions encouraged participants to recognize the anomaly, generate possible explanations, and consider the origin and processing of the material. Participants worked individually and were explicitly guided to formulate hypotheses, without being provided additional evidence or corrective feedback. The study employed the following case scenario:

The tomb of the Egyptian pharaoh Tutankhamun, who ruled between 1332 and 1323 BCE, was discovered in 1922 by archaeologist Howard Carter. Among the many valuable artifacts found in the tomb, one object particularly surprised scientists: a dagger made of iron.

This dagger can be considered an anomaly, meaning an extraordinary case, according to historical records. This is because, based on known sources, humans only began processing iron about 500 years later. This raises several intriguing questions:

- *How were the Egyptians able to work with iron before the Iron Age?*
- *Where did the raw material for this dagger come from?*
- *How did the Egyptians obtain this material?*

Analytical Framework

Participants' written responses were analysed using a Hypothetico–Deductive Reasoning (HDR) framework, which conceptualizes scientific inquiry as the coordinated generation, testing, and evaluation of alternative explanations. According to this perspective, science involves formulating competing hypotheses and deducing consequences that can be tested against evidence, a process that characterizes sophisticated scientific reasoning (Lawson, 2000; Lawson, 2008). This HDR approach has also been elaborated as a cognitive foundation for science learning, with hypothetical thinking constituting a central mode of reasoning employed by both scientists and learners (Kalinowski & Pelakh, 2023). The HDR framework guided the analysis of key inquiry steps, including anomaly recognition, hypothesis generation, use of evidence, and hypothesis evaluation.

- Observation and problem identification
    - Do the pre-service teachers recognize the iron dagger as an anomaly?

- Do they acknowledge that it challenges established historical knowledge?

- Hypothesis generation
  - Do they propose explanations based on prior knowledge (e.g., meteoric iron, early metallurgy, trade)?
  - Do they suggest multiple possible explanations or fixate on one?
- Use of evidence
  - Do they support their explanations with historical, chemical, or archaeological evidence?
  - Do they reference known facts, studies, or historical records?
- Hypothesis evaluation
  - Do they compare alternative explanations or assess their plausibility based on available evidence?
- Logical consistency in reasoning
  - Do they maintain coherent and logically structured reasoning across observation, hypothesis, and evidence?

Although the analytic framework was grounded primarily in hypothetico–deductive reasoning, elements of the Claim–Evidence–Reasoning (CER) framework (McNeill et al., 2006) were used as a supporting interpretive lens to examine how participants structured their explanations. Within this lens, hypotheses were treated as claims, references to historical or scientific information as evidence, and the logical connections between claims and evidence as reasoning. Consistent with Gotwals et al. (2012), this approach supported the analysis of participants' ability to construct evidence-based explanations within the broader inquiry process.

The framework draws on established models of scientific inquiry that conceptualize inquiry as a coordinated process involving problem recognition, explanatory construction, and evidentiary reasoning (National Research Council [NRC], 2012). The hypothesis revision stage was intentionally excluded, as the purpose of the study was to examine participants' initial explanatory reasoning rather than learning progression.

Rubric Development And Scoring

A four-level analytic rubric (Table 1) was developed to evaluate participants' engagement in scientific inquiry across five criteria. Rubric-based assessment is widely recognized as an effective method for evaluating complex cognitive practices such as scientific reasoning and inquiry, as it allows for systematic yet nuanced analysis of qualitative responses (Jonsson & Svingby, 2007). Each criterion was scored from 0 (absent) to 3 (proficient), yielding a maximum total score of 15. Aggregate scores were interpreted using predefined engagement levels (no, minimal, basic, developing, proficient), categorizing inquiry performance along developmental continua.

The responses of the participating pre-service teachers were evaluated based on each criterion, and the scoring was interpreted as follows:

Scoring Interpretation

- **0 points** →No Engagement in Scientific Inquiry
- **1- 5 points** → Minimal Engagement in Scientific Inquiry (Lacks understanding, weak reasoning, no use of evidence).

- **6 - 10 points** → Basic Scientific Inquiry (Some reasoning present but lacks depth and evaluation of evidence).
- **11 - 14 points** → Developing Scientific Inquiry (Good reasoning, considers evidence but lacks full hypothesis testing).
- **15 points** → Proficient Scientific Inquiry (Strong reasoning, effective hypothesis testing, and evaluation based on evidence).

Table 1. Rubric Criteria and Scoring

Category	Score: 0 (Absent)	Score: 1 (Basic/Naïve)	Score: 2 (Developing)	Score: 3 (Proficient/Advanced)
1. Observation & Problem Identification	Does not recognize the scientific anomaly or problem.	Recognizes the problem but describes it vaguely or inaccurately.	Identifies the problem with some clarity but lacks depth in recognizing its significance.	Clearly identifies the anomaly and articulates why it challenges established scientific knowledge.
2. Hypothesis Generation	No hypothesis is proposed.	Proposes a single hypothesis, but it lacks scientific basis or is a misconception.	Proposes one or more hypotheses with some scientific validity but lacks depth in justification.	Generates multiple plausible hypotheses, supported by logical reasoning and prior knowledge.
3. Use of Evidence (Empirical & Historical)	No evidence is provided to support hypotheses.	Mentions some evidence but does not connect it logically to the hypotheses.	Uses relevant evidence but does not fully explain its significance.	Uses strong, diverse evidence (chemical, historical, archaeological) and logically connects it to hypotheses.
4. Hypothesis Testing & Evaluation	Does not attempt to test or evaluate hypotheses.	Accepts a hypothesis without questioning its validity.	Considers alternative explanations but does not critically evaluate them.	Compares multiple hypotheses and evaluates them based on evidence, revising as needed.
5. Logical Consistency in Reasoning	No clear logical connections between problems, hypothesis, and evidence.	Some logical connections exist but contain gaps or inconsistencies.	Reasoning is mostly logical, but there are minor gaps or weak connections.	Uses well-structured, consistent reasoning that clearly connects the problem, hypotheses, and evidence.

Data Analysis

All participant responses were independently evaluated using the rubric. Scores were first examined descriptively to determine overall engagement patterns, followed by qualitative analysis to identify recurring strengths and weaknesses in scientific reasoning, including reliance on mechanistic explanations versus speculative or pseudoscientific claims. Combining rubric scores with qualitative interpretation is recommended for maintaining analytic rigor while preserving the explanatory richness of participants' reasoning (Miles et al., 2020).

By integrating an anomalous historical case with a structured inquiry rubric, this methodology enables systematic examination of pre-service teachers' initial scientific reasoning, particularly their capacity to generate causal explanations and use evidence.

Findings

Levels Of Scientific Inquiry Engagement

Analysis of pre-service teachers' responses using the Scientific Inquiry rubric revealed that the

majority of participants demonstrated limited engagement in scientific inquiry (Table 2). Specifically, 59 of the 62 pre-service teachers (94%) were categorized at the Minimal or Basic inquiry levels, indicating difficulties in coordinating hypotheses, evidence, and reasoning. Only two participants (3%) reached Developing or Proficient levels, while one participant showed no engagement.

Table 2. Pre-service teachers Scientific Inquiry Engagement Levels

Engagement Level	Number of Pre-Service Teachers (N=62)
No Engagement in Scientific Inquiry	1
Minimal Engagement in Scientific Inquiry	29
Basic Engagement in Scientific Inquiry	30
Developing Scientific Inquiry	1
Proficient Scientific Inquiry	1

Participants at the *Minimal Inquiry* level often recognized the historical tension but failed to articulate underlying mechanisms or evaluate evidence. For example, one participant stated, *"History is not a discipline with definitive conclusions… the Egyptians may have discovered iron-processing techniques before everyone else"* (PS2), offering a generalized claim without evidentiary support. Similarly, PS4 acknowledged uncertainty and provided no causal explanation: *"I have no idea where the iron was sourced from."*

In contrast, participants at the *Basic Inquiry* level proposed plausible explanations but demonstrated weak reasoning or incomplete use of evidence. For instance, PS9 suggested early technological advancement—*"Egyptian society may have started processing iron earlier"*—yet did not explain how such processing could have been achieved under known technological constraints of the period. Many responses in this category relied on assertions rather than mechanistic reasoning, such as PS21's statement, *"They may have made the dagger by hammering the iron."*

Only a small number of participants demonstrated *Developing or Proficient Inquiry,* characterized by coherent hypothesis generation, explicit recognition of the anomaly, and coordinated use of historical and chemical evidence. One high-scoring participant clearly articulated the anomaly and supported a mechanistic explanation:

> *"This information calls historical records into question because iron-processing technologies were not widespread in the 14th century BCE. However, the dagger found in Tutankhamun's tomb represents an anomaly indicating that iron was somehow processed during this period. One of the most plausible hypotheses is that the dagger was made from meteoritic iron, as chemical analyses have shown a high nickel content"* (PS1).

Types Of Hypotheses Generated

Across all responses, pre-service teachers generated 15 distinct hypotheses to explain the presence of the iron dagger in Tutankhamun's tomb (Table 3). These hypotheses varied considerably in scientific plausibility, ranging from evidence-based explanations to explicitly pseudoscientific claims.

Scientifically Plausible Hypotheses

As presented in Table 3, eight hypotheses reflected scientifically testable explanations, most commonly invoking meteoritic iron, early metalworking techniques, or trade. Several participants explicitly referenced meteorites as a feasible iron source:

Table 3. Hypothesis Frequency Table

	Hypotheses	Frequency	
1	The dagger was shaped using cold forging (hammering) techniques	9	Scienrific hypotheses
2	The dagger was obtained through trade from an advanced civilization that had early iron processing techniques	8	
3	The dagger suggests that iron was used earlier than currently recorded but not widely documented	7	
4	The dagger was processed using high-temperature furnaces or fire-based technique	6	
5	Egyptians unknowingly used iron without recognizing it as a distinct material	5	
6	Iron could have been processed in a different way, such as through exposure to natural environmental heat sources	4	
7	The dagger was created using metal that naturally formed in a way that made it easier to shape	3	
8	The dagger was made from meteoritic iron	2	
9	The dagger was placed in the tomb at a much later date	6	Non-scientific hypotheses
10	The dagger was melted and shaped by prolonged exposure to sunlight	5	
11	The dagger was made by a lost ancient civilization with superior technology	4	
12	The dagger was formed by lightning striking iron	3	
13	The dagger was made with the help of extraterrestrials	3	
14	The dagger was created using unknown supernatural or mystical forces	2	
15	The dagger was created using an unknown energy or method lost to history	2	

> *"It was most likely made from meteoric iron… people could shape the iron they found from meteorites by hammering it" (PS60).*

Others emphasized trade and intercultural exchange:

> *"As far as I know, the Egyptians were very advanced in many fields… they may have adopted ideas from other civilizations through trade" (PS33).*

However, even within scientifically oriented hypotheses, many participants struggled to articulate mechanisms, often stopping at surface-level claims without explaining how evidence supported their conclusions.

Pseudoscientific And Speculative Hypotheses

Seven hypotheses were classified as non-scientific, relying on supernatural forces, extraterrestrial intervention, or vague unknown energies. These explanations were typically devoid of evidence or causal reasoning. For example, PS13 stated, *"The dagger may have been made with magic,* "while PS52 suggested, *"I think the pyramids were built by extraterrestrials using more advanced technology."*

Such responses illustrate a tendency to substitute speculation for mechanistic explanation when causal reasoning was inaccessible, a pattern observed across minimal and basic inquiry levels.

Overall, the findings indicate that while many pre-service teachers were able to generate claims, far fewer were able to coordinate claims with evidence and mechanistic reasoning. Explanations frequently addressed why the dagger might exist (e.g., advanced civilization, historical uncertainty) rather than how it could have been produced given material and technological constraints.

Discussion And Conclusion

The findings indicate that most pre-service teachers were minimally or basically engaged in

scientific inquiry, despite generating a broad spectrum of reasoning approaches ranging from scientifically plausible hypotheses to pseudoscientific and speculative explanations. This variation highlights the pedagogical value of anomalous cases in teacher education, as anomalies are known to spark curiosity, challenge learners' prior assumptions, and foreground how evidence is interpreted and used in scientific reasoning (Chinn & Brewer, 1993; Allchin, 2013). Tasks based on anomalies can therefore function as diagnostic tools, enabling instructors to identify misconceptions and epistemic weaknesses early and to determine where instructional scaffolding is most needed (Echevarria, 2003; Windschitl et al., 2012). Moreover, historically grounded anomalies connect science with history, culture, and ethical considerations, making them powerful contexts for teaching the nature of science (NOS) as a human and socially embedded endeavor (Allchin, 2013; Matthews, 2015). Engaging with historical scientific mysteries may help pre-service teachers develop an understanding of science as a dynamic and evolving process, rather than a fixed collection of facts (Lederman et al., 2013). A limitation of the present study is that it did not include a hypothesis revision stage, which is widely regarded as essential for promoting sustained scientific inquiry and hypothetico–deductive reasoning (Lawson, 2009; NRC, 2012). Future studies should therefore provide pre-service teachers with successive evidence that allows them to revisit and revise their initial hypotheses, thereby more fully supporting the development of scientific reasoning.

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How Do Upper Secondary Greek Students View The Nature Of Science? The Case Of Chemistry

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Nature of Science (NOS) refers to science as a way of thinking along with the intrinsic beliefs and values related to scientific knowledge and its development. Taking into account the distinct and common characteristics of the different science disciplines, NOS is conceptualized as both general and domain specific. In this work, the views of Greek upper secondary school students regarding the different aspects of NOS were investigated, by taking the chemistry discipline as a characteristic case. An adapted version of the "Views of Nature of Science Questionnaire – Form C" (VNOS-C) instrument was employed and the responses of 96 students (16-17 y) were analysed qualitatively via the criteria of the VNOS Analysis and Scoring Rubric (VAScoR). A total of six NOS aspects were identified with students' views presenting a mixed picture regarding their VAScoR classification. For three NOS aspects - namely the myth of the "scientific method", tentative, and scientific theories – many partially informed views were identified. On the contrary, the naive views were a majority for the social and cultural embeddedness of science and with relatively frequent occurrence in the empirical and inferential NOS aspects. In addition, a quite large number of views regarding the empirical and inferential NOS aspects were classified as silent. The research findings provide insights into aspects of the chemistry curriculum and of the teaching approaches that need revaluation to enhance students' knowledge, skills and competencies with respect to the nature of science and promote chemical-scientific literacy.

Keywords: Domain-specific NOS, Domain general NOS, Nature of chemical laws

Introduction

Nature of science (NOS) has been an important educational objective for several decades and at the same time a significant topic in science education research. (Erduran et al., 2020; Abd-El-Khalick & Lederman, 2023). The discussion about the NOS construct among the research community and science educators, has provided several frameworks that aim to students' understandings of NOS for the promotion of scientific literacy. Several researchers have contributed to the conceptualization of NOS resulting in a set of some "general NOS aspects" or the consensus view of NOS (Abd-El-Khalick & Lederman, 2023). The term "consensus" should not be taken to imply full agreement on the framework. Although disagreements from a philosophical perspective and about the relations NOS with scientific inquiry or practices have largely been resolved, conversations about the "nature of NOS" still persist. These include critiques of the consensus view as being too general and arguments in favour of adopting domain-specific nature of science discipline, such as chemistry (e.g., Cetin et al., 2010).

According to the consensus framework, several lists that include a multitude of NOS aspects have been proposed. There exist, however, certain aspects, such as the empirical, tentative, creative, and scientific method, which are common in all lists (e.g. Lederman et al., 2002; Osborne et al., 2003), thus indicating that each one of these is related to a student's preconception about science (Kampourakis, 2016). These general NOS lists have been criticized as oversimplifying descriptions of science (e.g., Irzik & Nola, 2011). However, for school science, a simplified NOS view provides acceptable recommendations for NOS teaching and learning (Kampourakis, 2016).

An important discussion about NOS research which is considered crucial for secondary science education is related to the generality versus domain specificity of NOS. Some researchers have

argued that 'the consensual general NOS aspects are too broad and do not capture the heterogeneity of science subjects (e.g., Irzik and Nola 2011). For instance, the different features of laws in different science disciplines are not conceptualized. Specifically, some laws in chemistry, like in physics, are quantitative in nature (e.g. laws of stoichiometry), but others rely more on approximations without possessing quantitative expression (e.g. the periodic law).

Based on science disciplines' similarities and differences, the domain-general and domain-specific approaches could be considered as complementary (Kampourakis 2016). Therefore, general NOS aspects could provide a foundation for further development of domain-specific NOS learning in school science and further research on domain-specific NOS assessments is needed.

The inclusion of NOS in science curricula together with the increasing interest in corresponding science education research resulted in the development of various NOS assessments, which can be divided into two types: forced choice and open-ended. The theory driven forced-choice instruments are constituted of items along with their answers derived from various theoretical perspectives (Aikenhead et al., 1987). Therefore, students' responses might be biased toward one philosophical view and consequently not accurately expressing their thoughts (Abd-El-Khalick & Lederman, 2023). During the last two decades there has been a shift from forced choice to open-ended instruments with the Views of Nature of Science (VNOS) questionnaire being one which has been widely used (Abd-El-Khalick & Lederman, 2023).

There are, however, various concerns about the use of open-ended instruments. An analysis of responses is exhausting work that needs a thorough understanding of the NOS framework as well as more time and resources, particularly for large-scale studies. Moreover, the resulting data is not suitable for statistical testing of relations between various variables. Several researchers have proposed various ways to quantify responses to open-ended NOS instruments (e.g., Abd-El-Khalick et al., 2024, Burgin & Sadler, 2016).

The purpose of the present study is to investigate the NOS views of Greek upper secondary students by taking chemistry as characteristic case. The consensus view of NOS is used as theoretical framework to elicit and discuss students' NOS views as an attempt to combine both domain general and specific NOS views in an assessment. The study was guided by the following research question:

- How do Greek upper secondary students view the NOS in the context of chemistry?

Method

In this study, a descriptive qualitative approach was employed focused on measuring students' NOS conceptions based on the consensus framework in the chemistry context.

Participants

A total of 96 students of the 10th and 11th Grade (16 – 17 y) from one public school located in Athens (Greece) were participants in this study, using a convenience sampling procedure. The 10^{th} grade students have been involved in chemistry courses for 3 years and the 10^{th} graders for 4 years. Moreover, during chemistry courses they did not participate in any activity about nature of science. Students responded to instrument questions during a one-hour lesson of chemistry course.

Instrument

The instrument used (named VNOS-C-Ad and referring specifically to the chemistry discipline, Table 1) consisted of seven items and was an adaptation of the original VNOS–C (Lederman et al., 2002) questionnaire. The item of VNOS–C about the scientific laws was excluded from

VNOS-C-Ad because in chemistry courses students have been taught only the periodic law, which differs from others scientific laws. For example, the periodic law is not expressed mathematically as physics laws and the term "periodic" in the periodic law is not related to temporal periodicity as others scientific laws (Erduran, 2007; Scerri, & Worrall, 2001). The questions about organisms and dinosaurs of the original VNOS–C instrument were also excluded as they are related to biology. Finally, the items that relate creativity and imagination with experiments/investigations were excluded based on time limitation.

Table 1. The VNOS-C-Ad instrument.

1. What, in your view, is science?
2. What makes chemistry different from other disciplines, like philosophy?
3. What is an experiment?
4. Does the development of scientific knowledge require experiments?
If yes, explain why. Give an example to defend your position.
If no, explain why. Give an example to defend your position.
5. After scientists have developed a scientific theory (e.g., atomic theory), does the theory ever change?
If you believe that scientific theories do not change, explain why. Defend your answer with examples.
If you believe that scientific theories do change:
(a) Explain why theories change?
(b) Explain why we bother to learn scientific theories? Defend your answer with examples.
6. Chemistry textbooks often represent the atom as a central nucleus composed of protons (positively charged particles) and neutrons (neutral particles) with electrons (negatively charged particles) orbiting that nucleus. How certain are scientists about the structure of the atom? What specific evidence do you think scientists used to determine what an atom looks like?
7. Some claim that science is infused with social and cultural values. That is, science reflects the social and political values, philosophical assumptions, and intellectual norms of the culture in which it is practiced. Others claim that science is universal, that is, science transcends national and cultural boundaries and is not affected by social, political, and philosophical values, and intellectual norms of the culture in which it is practiced.
If you believe that science reflects social and cultural values, explain why. Defend your answer with examples.
If you believe that science is universal, explain why. Defend your answer with examples.

Data Analysis

The content validity of data is established during the first step of the analysis, where the target NOS aspect/s of each item were defined according to the literature (Lederman et al., 2002; Abd-El-Khalick et al., 2024). Then, students' responses were analysed in order to identify elements that justify their views of the NOS aspect and were classified to 4 categories as either informed (I), partially informed (P), naïve (N), and silent (S) according to the criteria of the VNOS Analysis and Scoring Rubric (VAScoR) (Abd-El-Khalick et al., 2024).

Table 4. The categories coding schema of students' views classification adopted from Abd-El-Khalick et al. (2024).

Category	Criteria
Informed view (I)	All elements of the target NOS aspect are judged to be informed
Partially informed view (P)	Only a subset of the core elements of the target NOS aspect are judged to be informed; and responses on other elements of the target NOS aspect are silent
Naïve view (N)	Either some or all elements of the target NOS aspect are naively addressed
Silent (S)	No relevant or irrelevant or incomprehensible or without reliable categorization response.

Two of the authors analysed the same responses of ten students, compared their analyses, and resolved discrepancies with the consensus of all authors to establish inter-rater reliability.

Results And Discussion

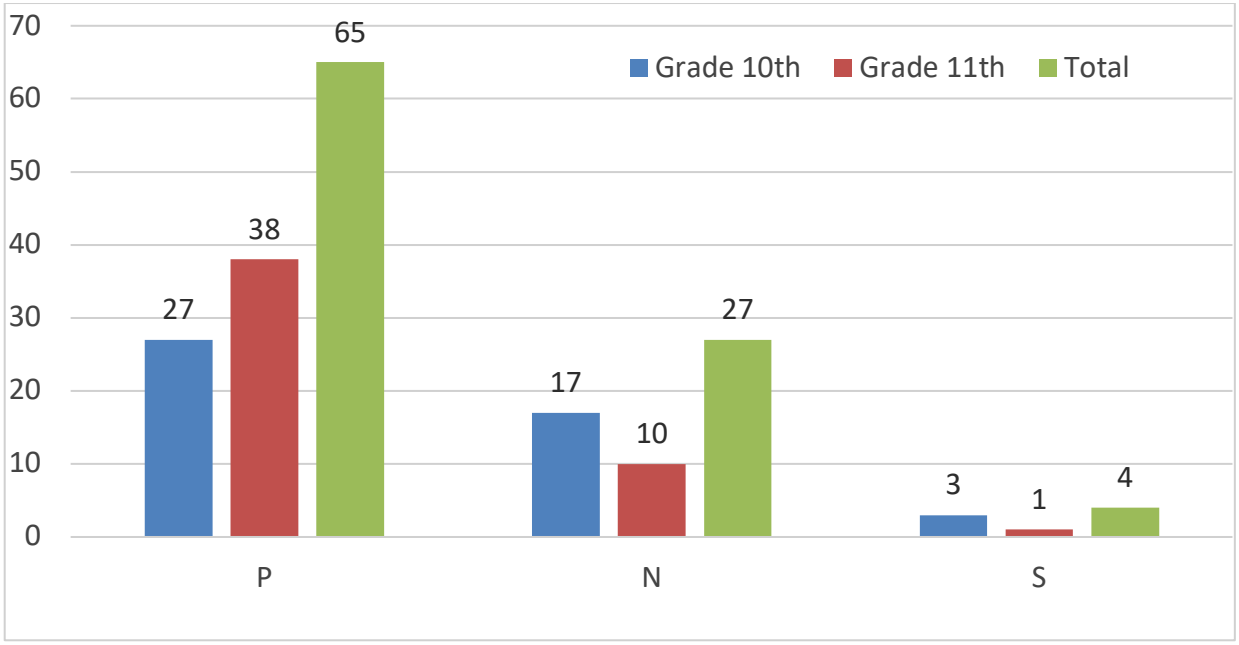
How Do Greek Upper Secondary Students View The Nos In The Context Of Chemistry?

Analysis of students' responses revealed the emergence of six NOS aspect/s: empirical, inferential, tentative, myth of "the scientific method", scientific theory, and social and cultural embeddedness of science.

How Do Students View Scientific Theories?

Students' views of the NOS aspect referring to scientific theories are mainly classified as partially informed (Figure 1).

Figure 1. Views of scientific theories aspect.



A representative quote showing a partially informed view is the following quote:

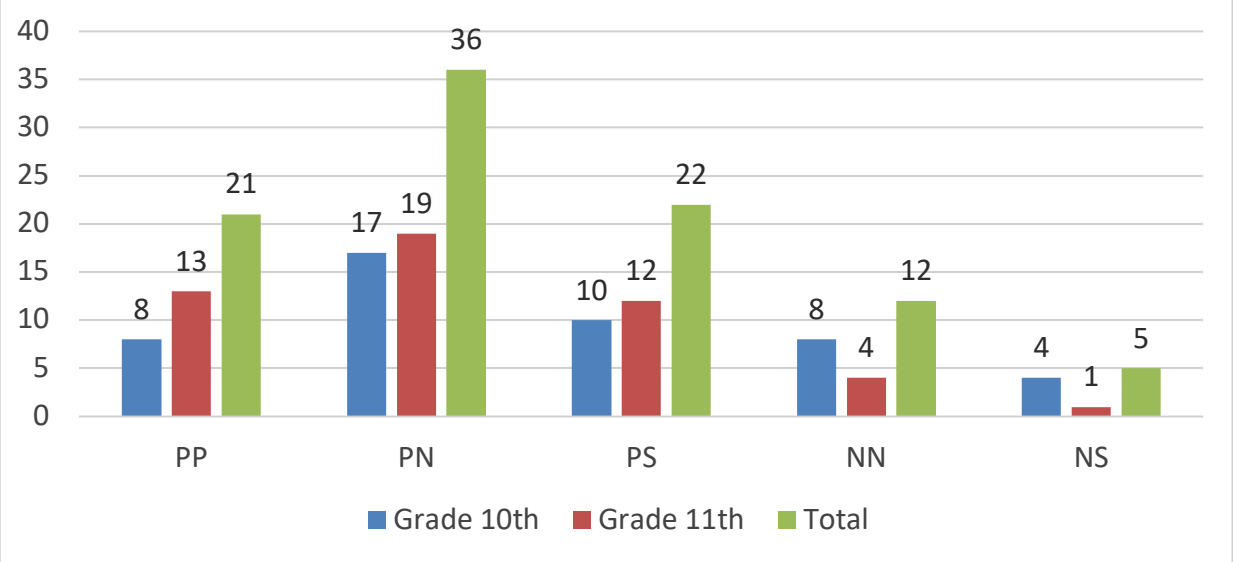
> Quote 1: "Since scientific theories have been confirmed using various means to prove their validity (e.g., microscopes for the structure of the atom), they are unlikely to change. They change if it is later proven, of course, that they are incorrect (this happens over time with the advancement of knowledge and technology)"

Do Students View Science As Tentative?

Students' responses to items 5 and 6 reveal the tentative NOS aspect and the distribution of their classifications are presented in Figure 2 (the first letter concerns the category of students' responses to item 5 and the second to item 6 respectively). The prevailing views in this case belonged to the category partially informed as 79 students express a partially informed view in at least one item. For example, students believe that conclusions arise from instruments (e.g., microscopes) rather than through reasoning (quote 2) Students with naïve views regard both scientists and the school curriculum as authoritative, containing absolute and unchanging knowledge about the physical world (quotes 3, 4)

> Quote 2: "Scientific theories change as scientific equipment improves. New tools allow for a deeper study of things, and as a result, sometimes the study uncovers new data that invalidate previous ones."

Figure 2. Views of tentative NOS aspect.



> Quote 3: "Scientists are very certain about the structure of the atom, as this theory has been proven to be true (through many experiments, other theories, and research) by previous scientists"

> Quote 4: "I believe they are quite certain (the scientists) for chemistry to be taught in schools."

As we can see in Figure 2, eleventh grade students also present more informed views than the ones in the 10th grade. Moreover, students' views of the tentative aspect seem to depend on the item.

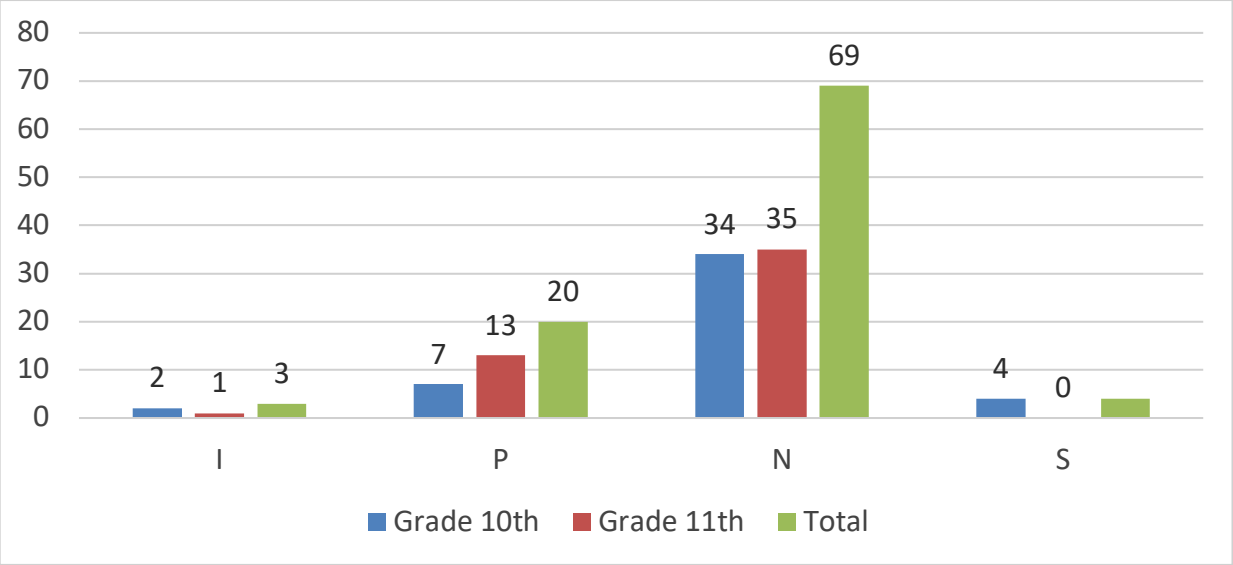
How Do Students View The Cultural Embeddedness Of Science?

Concerning the social and cultural embeddedness of science NOS aspect, 3 of the students' views are informed, 20 partially informed, and most of them (69) are naive views (Figure 3). Particularly characteristic examples of responses are presented by quotes 5 and 6.

Do Students View Science As Empirical And Inferential?

Figure 4 presents the classifications of students' views regarding the empirical (1st letter) and inferential (2nd letter) aspects. The views of the empirical NOS are classified as silent for most students (64), with the remaining students' responses being almost equally distributed between naive (15) and partially informed (17). Regarding the inferential NOS aspect most responses (67) are also classified as silent, 28 as naive and only one as partially informed.

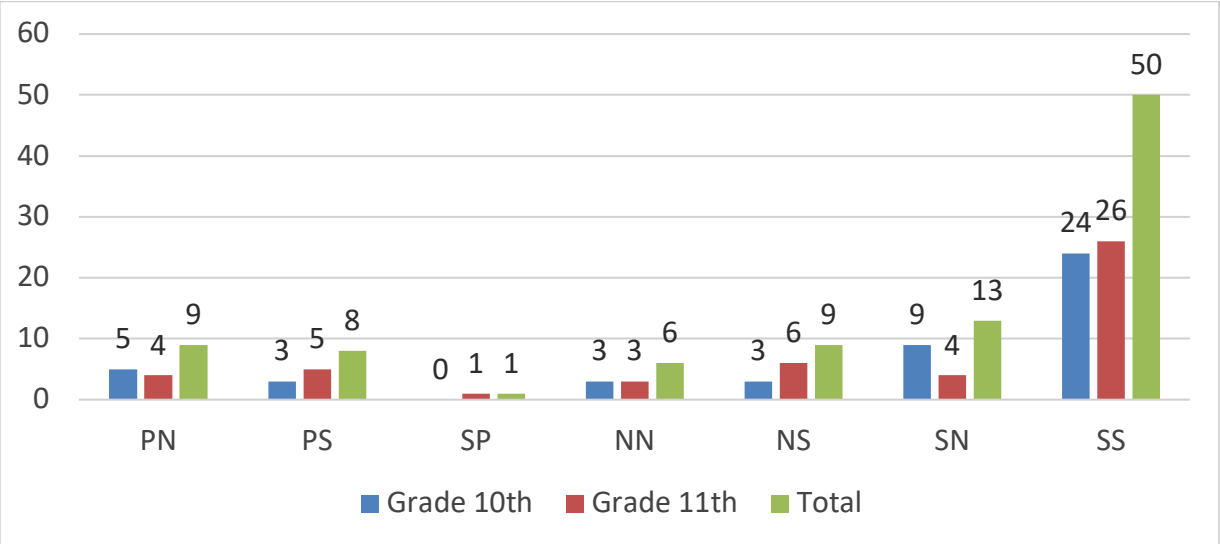
Figure 3. Views of social and cultural embeddedness of science aspect.



Quote 5: "I believe that science reflects the values of the culture from which it originates because these values determine the conditions under which it will develop. For example, it is much easier to study and develop controversial scientific fields in a progressive country than in a religion - centered country" (partially informed view).

Quote 6: "Science is universal, since we all live in the same space governed by the same physical and chemical laws. For example, atomic theory cannot be different in Europe and different in Asia because the culture and society are different" (naïve view).

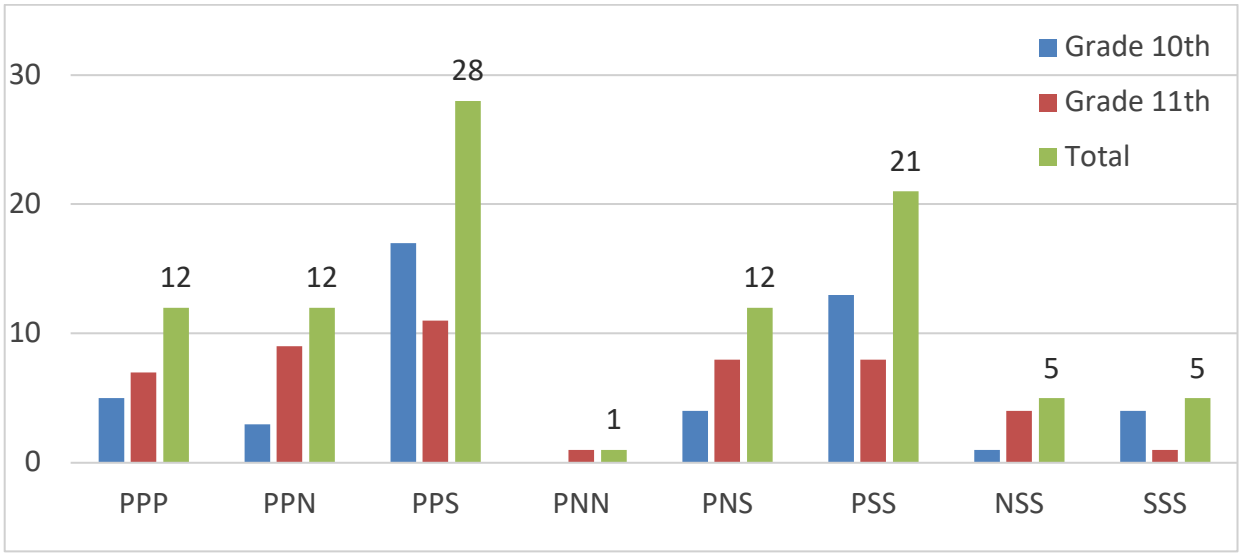
Figure 4. Views of empirical and inferential aspects.



How Do Students View "The Scientific Method"?

The myth of "the scientific method" aspect emerged from items 2, 3, 4 and the distribution of the classifications of students' views are presented in Figure 5. The first letter concerns the category of students' responses to item 2, the second to item 3 and the third to item 4, respectively.

Figure 5. Views of myth of "the scientific method" aspect.



Twelve students had consistent partially informed views (PPP), 40 students showed partially informed views in two items, and 31 students were silent in two or three items.

Interestingly, 11th grade students presented a shift to more informed views regarding the myth of "the scientific method", tentative, scientific theories as well as social and cultural embeddedness of science aspects (Figures 1-5).

Conclusions

This study used the example of chemistry as a specific science discipline to investigate Greek upper secondary students' NOS views. Six general NOS aspects were elicited from students' responses. A variety of classifications of students' views depending on the NOS aspect were revealed. Concerning the myth of the "scientific method", tentative, and scientific theories NOS aspects most students' presented partially informed views. On the contrary, the naive views were a majority for the social and cultural embeddedness of science and with relatively frequent occurrence in the empirical and inferential aspects.

This difference could be partially explained based on the Greek chemistry curriculum. Students are taught three models of atomic structure that were developed during different historical periods. Therefore, the example of atomic theory helps them express partially informed views regarding the "scientific method", tentative, and scientific theories NOS aspects.

Many students' responses regarding the empirical and inferential NOS aspects were irrelevant or incomprehensible and were classified as silent views. This indicates that traditional lab work in chemistry teaching is not sufficient for achieving meaningful NOS learning. Moreover, it could be related to the reduced students' ability to express their conceptions in writing in an open-ended instrument.

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Arguing With Eugenics: Brazilian Reasoning About Inheritance In The Late 1920s

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This work contributes to the promotion of scientific literacy focused on social transformation by analysing conceptual and epistemic aspects of Brazilian eugenics. To this end, we present a documentary analysis of the first year of the Boletim de Eugenia (Eugenics Bulletin), one of the documents used to promote eugenics in Brazil. The analysis focus on how the conceptual and epistemic aspects are mobilized to support eugenics ideas. In our findings, concepts such as inheritance are central to justifying eugenics artificial selection but the reasoning is flawed. We argue that the historical case of eugenics is fruitful in science education for raising discussions on how science is not a neutral endeavour and in promoting scientific literacy focused on social transformation. Eugenics case allows discussing science as a social endeavour, highlighting ways to produce, evaluate and legitimize scientific knowledge, as well as the discussion of social and ethical limits of scientific knowledge.

Keywords: scientific literacy; history of science; scientific argumentation.

Introduction

Valladares (2021) claims Scientific Literacy (SL), from an emancipatory perspective, can be understood both as a social practice and as a tool for the self-construction of one's voice and place in the world. Students educated from this perspective should be committed to social transformation and capable of taking advantage of science and other cultural knowledge - being aware of science's potentials and limitations - in the generation of adaptative, resilient, and sustainable responses to the challenges of the twenty-first century (Valladares, 2021). Accordingly, this contemporary perspective of SL takes cultural pluralism into consideration, is oriented toward social transformation (Valladares, 2021; Guerrero et al., 2025), and is committed to social activism, realized through students' participation and emancipation (Valladares, 2021).

As highlighted above, the social activism proposed in this framework seeks to address the multiple systemic and structural forms of violence that violate human rights on a global scale in the twenty-first century, a context marked by a profound human, political, and environmental crises. However, these crises do not affect society uniformly, as oppressive structures (mainly racism, sexism, and classism) exclude certain minoritized social groups in favour of dominant ones. We agree with the arguments portrayed by Valladares (2021) and Silva and Sasseron (2021) regarding the importance of Science Education in helping us understand how differential access to science and the unequal consequences of the scientific enterprise perpetuate historical inequities, and how the production of scientific knowledge must be oriented toward reducing these disparities.

According to Guerrero et al. (2025), SL constitutes a "transformative and socio-ecojustice-oriented framework that moves beyond content knowledge and scientific competence to foster

political agency, eco-reflexivity, and collective action" (Guerrero et al., 2025, p. 2). Thus, SL for social transformation highlights the importance of addressing socially relevant issues that enable the problematization of social injustices and inequities that are, to some extent, connected to science. Therefore, Science Education must address scientific laws and concepts allied with discussions about social scientific issues, as well as the epistemic, social, and material aspects of scientific knowledge (Silva & Sasseron, 2021). Considering ideas discussed by Duschl (2008) and Stroupe (2015), conceptual aspects are the knowledge developed by the scientific community; epistemic aspects are the criteria and norms used by scientists to determine what they know and why they know it; social aspects are the social processes by which scientific knowledge is produced, represented, and discussed; and the material aspects as the tools and technologies, along with their mode of use, applied in scientific investigation. This formative goal of SL, which goes beyond traditional content knowledge, can be achieved through different teaching approaches in which students engage with the social practices of science and, in doing so, learn about science (Silva & Sasseron, 2021). Guerrero et al. (2025) complement this discussion highlighting the importance of cross-disciplinarity and history-philosophy-sociology of science (HPSS) perspectives in the promotion of SL, especially of the critical and transformative aspect of it.

The use of History, Philosophy, and Sociology of Science (HPSS) in Science Education has long been recognized as a valuable means of presenting science as a form of knowledge that is socially produced and embedded in historical, social, economic, and political contexts (Allchin, 2013; Allchin et al., 2014; Forato et al., 2011). In this sense, numerous studies argue that HPSS can promote teaching about science, often referred to as the Nature of Science, converging to the transformative SL. However, the political and social inflections are still not explicit in this traditional justification to the use of HPSS in teaching. Moura (2025) recently pieced together proposals of a sociopolitical turn in Science Education that converges to SL for social transformation and recent literature has increasingly advocated for more politicized and politicizing uses of HPSS in Science Education.

For example, Moura (2021) discusses the potential of the use of HPSS to address historical processes of epistemicide, the plundering of knowledge, and the erasure of contributions from certain groups due to classist, racist, sexist, and colonial structures of oppression in the context of Science Education. He proposes it can be used to repair these harms since it unravels marginalized figures and suppressed forms of knowledge that can then be highlighted in Science classrooms. Similarly, Guerra and Moura (2022) propose expanding the traditional meanings of humanization and contextualization typically associated with HPSS in Science Education. Drawing on History of Science, they argue that, beyond being a human endeavour, science was produced in a global context by people of diverse origins and ethnic backgrounds and advocate that this should be highlighted in Science Education to expand student's perception of who can make science and from what places they come from. They also argue that it is important to problematize in Science classrooms that many of these contributors had their work erased due to the entanglement of modern science with colonialism, patriarchy, and capitalism. Both proposals for sociopolitical turn in HPSS (Moura, 2021 and Guerra & Moura, 2022) converge in their use of HPSS to problematize and repair the colonial erasures produced by modern science. In other words, they articulate HPSS as a pathway for promoting decolonial education in Science Education, and to foster antiracist approaches in Science classrooms (Pinheiro, 2023).

Once modern science has not only reproduced but also helped establish and justify racist and colonial power structures – such as through the development of race as a biological concept, social Darwinism, and eugenics – we argue that it's important that Science Education community investigates these historical episodes, so they can be discussed within an antiracist, justice-

oriented and transformative SL framework. To contribute to this end, this paper examines a major journal on eugenics from the late 1920s in Brazil. The aim of this work is to analyse inconsistencies in the mobilization of conceptual and epistemic aspects of science to support eugenic ideas in Brazil in the early 20th century and map the implications to Science Education.

Eugenics As A Case Of History Of Science

Eugenics was coined in 1883 by Francis Galton (1822-1911) in England, after he and other colleagues had been discussing the "problems" with migration and the poor classes of London. The movement proposed that the "improvement" of the human race (Singleton, 2014) could occur by promoting the perpetuation of traits deemed "superior" and restricting the transmission of traits associated with supposedly "inferior" individuals (Santos et al., 2014). Emerging during the period of disciplinary consolidation of modern science, eugenics held scientific status for decades (Diwan, 2007) and perpetuated racism as a result of the difference of races (biological at that point). To define which traits were desirable, the definitions were rooted in the English elite bias and were marked by racist assumptions (Zuberi, 2023). This framework ultimately reinforced hierarchical classifications of human groups and exclusionary policies of reproductive control.

Galton formulated eugenics as a way of justifying and addressing the social problems confronting the nineteenth-century English industrial bourgeoisie (Góes, 2015). Working-class neighbourhoods suffered from intense poverty and its associated social challenges. Galton attributed biological origins to behaviours, naming poverty, delinquency, prostitution, and mental illness, as the acts of "degenerate" people, arguing that physical, intellectual, moral, and psychological traits were hereditary (Góes, 2015). Galton claimed that the recent concepts of evolution could "help" eliminate the "degenerate" individuals and improve the species. In this sense, discussing eugenics might be fruitful to promote discussions about the goals of science as a potentially biased enterprise.

Today, we understand eugenics ideas are indefensible, still they were pervasive to the point of guiding public policies in various countries (Goés, 2015). One of the most known influences of the eugenics movement was the Nazi regime, with it's genocide practices (Stepan, 2005). In the United States, the eugenics movement developed a specially radical aspect, marked by segregation and sterilization laws and practices (Singleton, 2014). In Brazil, we highlight racist immigration policies that, in the beginning of the XX century, intended to minimize the immigration from non-European countries, and maximize the European "stock" aiming at whitening the population (Nascimento, 2016). Besides that, Brazilian federal constitution of 1934 explicitly advocated for a eugenic education in its Article 138, subsection (b) (Brazil, 1934).

In general, eugenics reasoning included i. the identification of "normative" individuals or individuals arbitrarily considered inferior; ii. the classification of individuals into groups according to shared characteristics (phenotypic or moral/behavioral); iii. the hierarchization of these groups; and iv. the symbolic or physical exclusion of groups considered inferior from the process of reproduction (Miranda, 2025). Despite these general aspects that characterize eugenic reasoning, eugenic ideas presented themselves in specific contours depending on the contexts in which they were produced and appropriated (Góes, 2015), therefore the eugenics movement cannot be treated or investigated as universal or uniform.

Eugenics ideology continues to influence practices in current society to the extent of possible uses for DNA and heritage exams, genetic counselling, artificial insemination, fertility control policies, and the persistence of the biologisation of social relations in research within the field of psychology on human behaviour (Góes, 2023). That's why Science Education should address and problematize eugenic ideas, then students become able to participate in the social debates

regarding themes, either directly or indirectly, related to eugenics. Therefore, we argue that it is important that Science Education research analyse how the conceptual and epistemic aspects of science were mobilized to support eugenics so that we can help students criticize similar ideas that may rise in current days and prevent the reinforcement of eugenics and deterministic reasoning through Science Education.

Methods

The research approach adopted was qualitative, prioritizing an in-depth analysis of a phenomenon (Creswell & Creswell, 2023), in this case, the ways in which conceptual and epistemic aspects were inconsistently mobilized to support eugenic ideas in Brazil. This study is characterized as documentary research, which aims to contribute to the understanding of a community or phenomenon situated in a specific time and place (Fontana & Pereira, 2023).

We selected texts from the first year of the Eugenics Bulletin (Boletim de Eugenia – BE), a journal designed by Renato Kehl that circulated in Brazil between 1929 and 1933, disseminating and promoting eugenics in the country. The journal included thematic sections related to politics, education, manners, science, and health, which sought to legitimize eugenics as a scientific field of study. The BE had a central role in introducing eugenic reasoning in Brazil and its future ramifications (Maciel, 1999; Góes, 2015). The texts were accessed electronically through the Brazilian Digital Newspaper Library (Hemeroteca Digital Brasileira).

For the analysis, we selected all articles published in the 1929 issues of the BE available at the repository, a total of 105 articles. Initially, we conducted a full reading of the articles, identifying excerpts that evidenced the inconsistent mobilization of conceptual or epistemic aspects of the Natural Sciences to justify eugenic ideas disseminated in the BE. The presence of disciplinary concepts in the excerpts was used as cue to conceptual aspects, while epistemic aspects were identified through the presence of scientific or purportedly scientific arguments. Each article was analysed by at least two of the authors.

Following the initial survey, 28 articles were selected in which the arguments presented contained conceptual errors, and logical or material inconsistencies. We did not consider arguments in which the concepts were mobilized correctly, since the focus of the analysis is on the misuse of science to support eugenic ideas. The evaluation of the correctness of concept usage took into account the scientific standards of the period, in order to avoid anachronistic analyses. As the final step in constructing the analytical corpus, we selected, from the 28 articles, only those in which the mobilized biological concepts were in some way defined or exemplified in terms of their application. This resulted in a final selection of 20 articles.

Finally, the conceptual and argumentative inconsistencies were made explicit in a descriptive-argumentative text, interspersed with excerpts from the BE that illustrate these inconsistencies, forming the basis of our results and discussion. These stages were carried out by a group of six researchers in the field of Science Education, aiming at validating both the construction of the corpus of analysis and the analytical process.

Results and Discussions

According to the BE, eugenics is a science that aims

> [...] to cooperate for the progressive increase of physically, psychically and morally healthy men; for the gradual reduction of the contingent of the weak, sick and degenerate, thus contributing to the constitution of [...] in short, a balanced humanity, composed of strong and beautiful individuals, elements of peace and work (Kehl, 1929, n.4, p. 1, translated from Brazilian Portuguese - BP).

As published, the purpose of eugenics is to promote an alleged improvement of the human species through selecting individuals who are deemed to be "well-endowed", "superior" or "eugenic".

The **biological concepts** identified in the BE's articles were heredity, inheritance, artificial selection, and natural selection. These are crucial concepts to eugenics. In some excerpts, the BE explicitly acknowledges eugenics as a process of **artificial selection**:

> Who doesn't know what crossbreeding and seed selection mean for a plant? I have seen forests of fantastic beauty in Brazil [...] but their orchids were not as beautiful as the orchids that, through artificial selection, acquire truly extraordinary form and development in Brazilian gardens. [...] These selective practices are applicable to the human species. It has been proven that crosses between superior breeds produce superior types, and vice versa (Recasens, 1929, n. 4, p. 2, translated from BP).

Here we highlight the subtlety in suggesting artificial selection as a tool for "improving" the human race. Although the word "artificial" is not directly used, the expression "selective practices" is used in a synonym meaning, as it suggests selective breeding, that was inflicted by the eugenics movement through the control of human reproduction or killing.

Artificial selection is presented as a solution to the alleged inability of **natural selection** alone to contribute to the improvement of the human species. The defence of this idea becomes evident in the following excerpt: "*It [eugenics] will do everything in its power to halt reverse biological selection in contemporary society, and everything that may serve to support the vigorous natural selection that so actively contributes to the preservation of the most capable*" ("*eugenia e alcoolismo"*, 1929, n. 8, p. 5, translated from BP). Francis Galton, proposed similar ideas in the first book in which he uses the term "eugenic". According to him, in civilized societies, humanity does not experience the effect of natural selection the same way:

> His ["man's"] character is exceedingly complex, even in members of the simplest and purest savage race; much more is it so in civilized races, who have long since been exempted from the full rigor of natural selection, and have become more mongrel in their breed than any other animal on the face of the earth (Galton, 1883, p. 178).

In addition to proposing **artificial selection**, the BE also provided indications of how to implement it, in articles such as *The Selection of the Well-Endowed* (Decroly, n. 10, 1929). Also, **artificial selection** is closely related to the importance given to inheritance since these texts emphasized the importance of considering the role of **heredity** and environment in determining individual superiority, so that the most "fit" could be selected (Decroly, n. 10, 1929). Similar discussions are found in the chapter *Nurture and Nature* by Galton (1883). This implies that both in Brazil and England discussion on the relative importance of the environment and inheritance in determining people's characteristics were relevant to the eugenics movement. Differences rise though regarding the emphasis given to each factor in each context. In both cases, we observe the attribution of great importance to inheritance, once to be selected characteristics must be inheritable. Although in Latin countries, in general, a little more relevance is given to the environment (Stepan, 2015). Because of the ethnic constitution of Brazil, it would not be possible to prevent races deemed inferior from reproducing. As a result, in Brazil, interracial reproduction arises as a eugenics strategy (Góes, 2015) and there is an overlap between eugenics (focus on inheritance) and hygienism in Brazil (focus on bettering the environment) (Maciel, 1999).

Recognizing that eugenics proposed artificial selection is important for two reasons. First, it reveals the arbitrariness underlying eugenics, manifested in the fact that "good" characteristics – those considered to make individuals more suited to civilization – were selected arbitrarily rather than in relation to the natural environment, as proposed in Darwinian evolutionary thought.

Second, artificial selection is the reason why such importance is given to **heredity** and **inheritance** in eugenics reasoning. According to the BE, the aim of studying biological inheritance would be "*discovering the laws of inheritance and consciously applying them to the improvement of human offspring*" (Huerta, 1929, n. 8, p. 2, translated from BP). In other words, eugenics sets out to study the inheritance of characteristics, so that they can then be selected.

The primary importance attributed to **heredity** is further justified by the fact that, within eugenics reasoning, heredity was responsible for the continuity of characteristics across generations, whereas differences between one generation and another were understood as a result from environmental influence: "*This does not mean, however, that our personal influence is null. Far from it, I think, the action of the environment and education can be enormous. Indeed, alongside the continuity of characteristics over time (heredity), there are also differences*" (Govaerts, 1929, n. 1, p. 4, translated from BP). This way of mobilizing **the role of the environment in the evolutionary process** differs from that proposed by Darwinian evolutionary thought at the time, which conceived the environment as a filter for existing variations rather than as a generator of disturbance and difference. Nevertheless, this concept was mobilized in such a way to justify the importance of identifying which inheritable characteristics should be selected.

In our analysis, we identified several articles that discussed whether certain characteristics were inheritable or not, including criminality, epilepsy, haemophilia, alcoholism, violent behaviour, docility (individuals considered amenable to education), and aptitude for specific sports, forms of art, or professions. These characteristics were pondered as parameters for **artificial selection**. Similar discussions can be found in the chapter *Criminals and the Insane* by Galton (1883). In both the BE and Galton's book the claimed inheritability of characteristics such as criminality and alcoholism is used to justify the control of human reproduction as social improvement. The biologisation of such human behaviours culminates in the naturalization of the social injustices that contribute to these behaviours.

Regarding the argumentative problems identified in the analysed arguments, there are inconsistencies such as the **presentation of a conclusion without evidence**, such as in "*This is why education comes up against, powerless, in many cases, failing to tame an untamed person, whose constitution is the result of an irremovable hereditary process. 'One is born good!'"* (Kehl, 1929, n. 9, p. 1, translated from BP). In the excerpt, the argument is made that not all individuals should be educated, based on the premise that some people are biologically undomesticable; however, no evidence is provided to support this claim. Also, this excerpt asserts that 'domesticability' is an inheritable characteristic, without defining what 'domesticability' is or presenting any evidence.

Other arguments are based on **confounding correlation for cause**:

> An investigation was carried out among 3000 English criminals in London prisons. With the help of Galton's correlation coefficient, Dr. Goering organized the similarity indices between criminals linked by kinship, coming to the conclusion that heredity plays a preponderant role in the transmission of these characteristics (Kehl, 1929, n. 5, p. 3, translated from BP).

The co-occurrence of two variables, in this case kinship and criminality, is taken as proof of a causal relation between the two variables, culminating in the conclusion that the characteristics are hereditary. In other words, if a father and son are both criminals, criminality is hereditary, and the son inherited his criminal inclination. The same type of argumentation is found in the chapter *Criminals and the Insane* by Galton (1883). This highlights the biologisation of social behaviour as an agenda of the eugenics movement both in Brazil and England. Besides, it demonstrates that,

in both cases, political agendas took precedence over scientific rigor in the construction of the arguments. This type of argument is presented for physical and moral characteristics, whether they are perceived as good or not:

> Mack Garner, a champion horse racer [...] tells an interesting story about the tendency of all the members of his family to pursue this profession. His father and grandfather were both jockeys [...] His four brothers were dedicated to the sport [...] One of his nephews is already a jockey and the other two, while still children, already have a special interest in everything to do with horses (Kehl, n. 10, 1929, p. 4, translated from BP).

It is also worth noting that none of the arguments present **alternative hypotheses** or **methodological details on how the evidence was gathered**, which is expected for validating reliable scientific claims. The only material aspect of the mode of production of scientific knowledge mobilized in the argument is the use of statistical data, employed in an anecdotal manner and insufficient to support the following conclusions. Thus, conceptual and epistemic aspects cannot be analysed separately, since arguments are responsible for guaranteeing that the way in which the concepts are produced, mobilized and used to draw conclusions is valid. This result reinforces the importance of taking this entanglement between the mobilization of epistemic and conceptual aspects to the context of Science Education.

Conclusion

Brazilian eugenics reasoning lacks evidence to justify its claims. Still, it sustained a myriad of discriminatory political and social actions and promoted a racist ideology. Brazilian eugenics used science to fulfil an agenda and the arguments or concepts used didn't even need to be sound for that, extrapolating disputed concepts for every convenient characteristic that could be used against non-white and poor people. Our analysis helps us understand that conceptual and epistemic aspects are not in a vacuum, and the ideas in the BE were the needed framework to legitimize elite's discrimination.

As we focused in the Brazilian context, the results of this study cannot be generalized as applicable or true to the eugenics movement in different countries. However, we identified some resemblance between Brazilian and English eugenics, from themes of study, theoretical propositions and premises to argumentative inconsistencies observed. Thus, we propose that Science Education research could benefit from further research regarding the conceptual and epistemological use of science to justify eugenics in different contexts. By doing so, we will be able to trace general aspects of these appropriations, revealing similarities among countries, and differences due to specific contexts and interests of each nation.

Despite the regionalized aspect of the analysis presented in this paper, we understand that some of the results allow the discussion of broad implications to the field of Science Education. First, we argue it would be fruitful to use the historical case of eugenics in the context of SL for social transformation, as the eugenics movement illustrates the social consequences of a biased and elitist scientific production allowing the discussion of the importance of a diverse scientific community to guarantee scientific objectivity. Second, we propose the use of the historical case of eugenics also makes it possible to discuss social aspects related to the production of scientific knowledge, showing that scientific production is not neutral, but a human production located in a historical and cultural space, producing and being influenced by the values in force in society (Silva & Sasseron, 2021). Third, we understand the historical case of eugenics highlights the importance of discussing the need of ethics and bioethics in science in science classrooms.

Regarding other implications to Science Education, we highlight the importance of promoting a historicized teaching of genetics and evolutionary biology. We understand that discussing the

eugenics movement could collaborate to the construction of a more complex and critical comprehension of the Nature of Science and of the role of science in society. Besides that, we argue for the importance in promoting a biology teaching that intentionally seeks to prevent the construction of deterministic ideas that align with eugenic reasoning and a teaching about evolutionary biology that differentiates biological evolution from biological or even social supposed improvement that is also a eugenic idea. We also believe that the poor scientific argumentation identified in the BE could be used to discuss what counts or doesn't as scientific evidence and how to build valid arguments. These skills are very important within a SL for social transformation framework.

In summary, the characteristics of eugenics highlighted by the analysis presented in this paper demonstrate the Historical case of eugenics is interesting to promote SL to social transformation since it allows the discussion of social political aspects related to science, either in an internalist manner - what counts or does not count as science, diversity in academia, ethics - or an externalist one - the social and historical character of science and the possible social consequences of scientific production.

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ESERA 2025 Copenhagen

Heritage And Transmission: A Reflection On The Origins And Development Of Didactics Of Science/Science Education Research

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The French journal RSDT-Recherches en Didactique de Sciences et des Technologies opened a call in 2025 to recruit contributions to reflect on the origins and development of the research field of didactics of science in France. It is 40 years since the first publication of the journal Aster, the first French journal for research in didactics of experimental sciences. This call, the 30th anniversary of ESERA, and the recent foundation of ESERA SIG9 on Histories of Science Education constitute an opportunity to start a shared reflection on the history of didactics of science/science education research. A general introduction for the western world and three cases from France, Luxembourg and Catalonia-Spain are presented focusing on the emergence of the field at either the country or the institution level. The aims of the symposium presented here are the following:(a) situating the origins of didactics of science/science education research in the context of the western world; (b) identifying the thematic changes in research programs during these years in different contexts. This paper concludes with a discussion on the commonalities and divergences arising from the drafting of a history of didactics of science/ science education research in the context of the countries represented -France, Luxembourg and Catalonia-Spain.

Keywords: Histories of Science Education, History of Didactics of Science, Case Studies.

Introduction

The French journal *RSDT-Recherches en Didactique de Sciences et des Technologies* opened a call last year to recruit several contributions to reflect on the origins and development of the field of research of didactics of science in France (Lhoste and Venturini 2025). It is 40 years since the first publication of the journal *Aster*, the first French journal for (scientific) research on didactics of experimental sciences. Such calls, in addition to the 30th anniversary of international association ESERA and the recent foundation of ESERA SIG9 on Histories of Science Education, constitute an opportunity to start a shared reflection on the history of didactics of science/science education research in different western countries, focusing on countries, institutions, research groups or individual researchers. The first aim of the symposium presented here was to situate the origins of didactics of science or science education research fields in the context of the western world through the following question: What have been the themes, the academic fields, the people, and the research groups that have contributed to the birth of our discipline in different western countries or institutions? The second aim of the symposium was to conduct an audit of the first results considering thematic changes throughout the years in different contexts. The question guiding this reflection has been the following: In what ways have the research questions, research approaches and results changed over these years in different western countries? The symposium discussed in this chapter was promoted by the recently created ESERA SIG9 Histories of Science Education, and we hope it will open the door to conduct more systematic historical inquiry within the science education research community worldwide.

The Emergence And Development Of Research In Didactics Of Science In The Years 1970-2000: A Focus On The Western World And France

The first contribution of the symposium addressed the first aim by examining the emergence of research in the didactics of science across Western countries and, within this context, the development of this field in France. For the whole symposium, this contribution provides a common ground useful for the positioning of the other three contributions situated in France, Luxembourg and Catalonia-Spain.

Renewal Of Science Teaching

To analyse this emergence in relation to the renewal of teaching, our framework includes some social components: the societal and institutional contexts, the social status of the actors involved, their objectives, the way they work in groups and the nature of their productions.

Societal And Institutional Contexts

Beginning in the 1950s–70s, Western countries began to reflect on the massification of education, driven by policymakers, academic societies, professional associations, and society demands. In France, in the fields of sciences and mathematics education, the Academy of Sciences, along with associations of mathematics teachers and later, associations of physics-chemistry and life and earth sciences teachers advocated for renewing secondary education. The evolution of the science teaching at secondary school level, spurred by these initiatives, was influenced by ministerial decisions and shaped by the broader French educational context.

The Designer Groups: Institutional Anchoring And Activities

Groups combining research and development, often involving researchers and teachers, were formed. These groups produced teaching resources and research findings with a particular focus on understanding students' learning difficulties. In most countries, the groups responsible for designing new teaching resources became, sooner or later, affiliated with university institutions. For instance, in France, the Lagarrigue ministerial commission established a working group led by physicist Goéry Delacôte. A few years later, this group evolved into a research laboratory called LIREST (*Laboratoire Interuniversitaire de Recherche sur l'Enseignement Scientifique et Technologique*) associated with a university in Paris and the National Center for Scientific Research (CNRS). A defining feature of designer groups was their collaborative nature where researchers and teachers worked together to design teaching resources. During this period, researchers and sometimes teachers with initial training in physics or chemistry also studied psychology (e.g. Dewey, Piaget) and shared constructivist perspectives.

Contribution Of Activities For Renewing Science Teaching To The Emergence Of Research In Didactics Of Science

The work on students' conceptual understanding was clearly linked to the development of research in didactics particularly in the domain often called students' conceptions. In addition, although the theoretical component was not highly developed, several results were replicated across different countries (Driver et al., 1985). The question of whether designing teaching materials is a research activity was less clear. According to Cobb et al. (2003), in research, "design experiments are conducted to develop theories, not merely to empirically tune 'what works'. These theories are relatively humble in that they target domain-specific learning processes" (ibid, p.9). In this sense, designing teaching materials at this time may not fully qualify as research. However, it incorporated research elements such as analysing the nature of the knowledge taught and the teaching goals, paving the way for the emergence of research such as design experiments

and design-based research.

In conclusion it is worth mentioning that government institutions and education systems, which initially supported the design of science teaching materials by designer groups affiliated with universities, some years later took the lead in modifying official curricula and planning. These changes were only partially nourished by the productions of the designer groups (French, 1986). Nonetheless, researchers involved in these productions and other researchers contributed to the creation of research associations, such as the European Science Education Research Association (ESERA) founded in April 1995 which remains active today.

Evolution Of Research Themes From Its Beginnings To The 2000S Based On ESERA Conferences

This presentation addresses the symposium's second aim with an analysis of the evolution of research themes from its beginnings to the 2000s, primarily based on the strands of the early ESERA conferences. This analysis is developed based on a generic structure, the didactic triangle with three poles, student, teacher, and teaching content and their interrelationships. This approach helps to put together research studies spread across the strands and highlights broader trends such as the decline in research on students' conceptions, the rise of studies on the nature of science, socio-scientific issues and science teaching practices in relation to enquiry-based learning. Beyond the triangle, two additional themes emerged: the first related to curriculum policy involving the education system, and the second focused on the state and the practices of research in science education. This brief analysis shows that researchers involved in developing teaching materials were also engaged - directly or through colleagues - in specific research themes. It also highlights that theorizing the activity of designing teaching resources requires more time probably because of the inherent complexity of teaching, the complexity of "learning ecology".

Case 1: The Origins Of Didactics Of Life And Earth Sciences In France: Groups, Institutions, Research Orientations

The first case is situated in the context of France and aims at looking back at the origins of a research discipline, the didactics of life and earth sciences in France in the second half of the 20th century. This contribution addresses the following themes and questions: (a) the key players in the emergence of this research discipline (Who are the protagonists in the emergence of this discipline? What are their functions? What are their intellectual filiations?); (b) the various institutions and contexts in which this early research took place (What groups contributed to the emergence of this discipline? What links are there with universities and academic research?) and (c) the first avenues of research explored by the first publications in the field of life and earth sciences didactics. (What are the initial research concerns? What avenues of research are opening? How are they unfolding?)

The Origins Of Life And Earth Sciences Didactics In The Pedagogical Reform Of The 1960S-1970S

The origins of the didactics of life and Earth sciences can be traced back to the pedagogical reform movements of the 1960s and 1970s (Kahn & D'Enfert, 2010). The central issue at stake was questioning of both the traditional school format and the organization of teaching. This critique of traditional education also involved a challenge to the empiricist and dogmatic vision of science education, which was prevalent in the "lesson of things" approach. As early as the 1960s, this challenge began to take shape in the pedagogical sphere (Kahn, 2000). This pedagogical reform led to the implementation of awakening activities in primary education (Best, 1973; Best, 2006). The first research in the didactics of life and Earth sciences was developed within the National Pedagogical Institute (IPN), led by Louis Legrand. In 1967, the field of educational sciences was

established within universities, and in 1969, Legrand created a didactics department within the IPN, which included a "science section" (later renamed "experimental sciences"). Victor Host, an associate professor of natural sciences involved in teacher training at normal schools, was appointed by Legrand in 1969 to lead this section. The research efforts were driven by awakening activities at the primary school level and experimental lower secondary schools (CES).

The Development Of The IPN Science Team And Action Research

With the transformation of the IPN (Institut Pédagogique National) into the INRP (Institut National de Recherche Pédagogique) in 1976, Jeanine Deunf, an inspector general of national education, led teacher training programs for *écoles normales* (teacher training schools) at the national level, fostering the development of action research. Many *école normale* professors contributed to this research, as evidenced by the list of contributors to the study *Procédures d'apprentissage en sciences expérimentales* mentioned in the journal *Aster* in 1985, and later published in 1998 under the title *Comment les enfants apprennent les sciences* (Astolfi et al., 1998). A subset of Victor Host team—comprising Jean-Pierre Astolfi, André Giordan, Gabriel Gohau, Victor Host, Jean-Louis Martinand, and Georges Zadounaïsky—published the first didactics book in the field of science education in 1978: *Quelle éducation scientifique, pour quelle société?* (Astolfi et al., 1978). The book's first chapter, with the evocative title *OHERIC ne répond plus? Le naufrage de l'éducation scientifique ?* ("OHERIC is no longer responding? The shipwreck of science education?"), written by A. Giordan, directly challenged the empiricist approach to scientific methods in schools. This team was also responsible for launching the journal *Aster*, published by the INRP from 1985 onward.

A Gradual Integration Into The Academic Sphere

Initially, the emerging community of didactics researchers did not readily accept academic engagement. However, Victor Host encouraged such involvement and established connections with Georges Canguilhem, a philosopher of biology. This led to the creation of a *Diplôme d'Études Approfondies* (DEA, equivalent to a master's degree) in didactics, with a specialization in biology education, environmental education, and later geology, at Paris 7 University in 1975, spearheaded by Christian Souchon and Victor Host. The program initially enrolled two students, Michèle Dupont and Guy Rumelhard, both of whom later joined the faculty as educators in 1979. The establishment of the *Instituts Universitaires de Formation des Maîtres* (IUFM) in 1991 facilitated the creation of the first faculty positions dedicated to research and teaching in life and Earth sciences didactics.

Research Themes

The foundational research themes in life and Earth sciences didactics emerged from the early work conducted at the IPN under the direction of Victor Host. Jean-Pierre Astolfi (2008, pp. 103–104) outlined the core issues that structured the initial research in this field: (a) The constant avoidance of verbalism and dogmatism; (b) The role of scientific attitudes; (c) The necessity of anchoring educational practices in children's spontaneous needs; (d) The importance of listening to students in order to understand the logic of their thinking; (e) The impact of students' conceptions of scientific knowledge on their future learning; (f) The requirements of conceptualization; (g) The diversity of levels of scientific concept formulation; (h) The construction of observational frameworks; (i) The central role of scientific problems; (j) The organization of scientific disciplines around a limited number of structuring paradigms; (k) The significance of the history and epistemology of science in addressing didactic challenges; and (l) The importance of written and graphical records in constructing scientific thought, distinguishing between the logic of discovery and the logic of communication.

Case 2: The Emergence Of Didactics Of Science As A Research Field At The Universitat Autònoma De Barcelona

This case aims at situating the origins of the Didactics of Science field at the Universitat Autònoma de Barcelona (UAB) in Catalonia, Spain, from the point of view of the actors participating in its emergence between 1970 and 1995. In the past, there have been several efforts to construct the history of science education research through different narrative approaches (Adúriz-Bravo and Izquierdo 2001; Fensham 2004). The work of Tobin and Roth (2007) is particularly useful for this contribution since they conceptualize the history of the field through the lenses of cultural sociology. The overarching methodological approach used in this contribution is compatible with autoethnography understood as both process and product (Ellis, Adams and Bochner 2011). This approach to research and writing seeks to describe and systematically analyse personal experience to understand cultural experience. The product is a collective narrative co-written by the three co-authors through an ongoing participatory process initiated in 2020. This process has involved a diversity of actors including students, retired professors, and active members of the Didactics of Mathematics and Experimental Sciences Department from UAB. The narrative is organized into two sections: (a) First phase (1970-1985) characterized by the growth of science teaching innovations and the institutionalization of science teacher education, and (b) Second phase (1985-1995) constituted by the processes and actions undertaken to become researchers in didactics of science.

Promoting Science Teaching Innovations And Science Teacher Education (1970-1985)

Spanish political context has always strongly influenced innovation in education as well as science education in Catalonia. Previously to the Spanish civil war starting in 1936 and during the Catalan Republic there was a strong political support to educational innovation based on the progressive ideas coming from continental Europe. These innovations were suddenly interrupted, strongly repressed and innovative schools closed during the dictatorship. Despite these difficulties, during the dictatorship, young teachers created new primary and secondary schools conducting innovations in science teaching. The three co-authors have been science teachers or students at these schools and participated in science teachers' groups with the aim of promoting teaching innovations. Several key Catalan institutions played a very important role in promoting and sustaining these *innovative science teachers' groups*. An example at the primary education level was the "Working Group for the Teaching of Science" hosted by Rosa Sensat Teachers Association and another example at the secondary education level was the "Didactics Center of Experimental Sciences" hosted by Col.legi de Doctors i Llicenciats.

Networking and internationalization were important factors influencing the emergence of our field at UAB. The first Spanish conference we ever participated was the I Simposium Internacional de Didáctica General y Didácticas Especiales held in la Manga del Mar Menor, Spain, September 27th-October 2nd, 1982. The first international conference we ever participated was the Journées Internationales de Chamonix, France, in 1987 (Sanmartí 1987). Both countries, UK and France, have been very influential on the emergence of our field in Catalonia and Spain. Finally, the *university status of science teacher education* became possible because of the General Education Law of 1970. Two years later it was founded the Escola Universitaria de Fromació del Professorat d'EGB at UAB, also known as Teachers' School of Sant Cugat, with the impulse of very committed and innovative science teachers, devoted to the training of infant and primary teachers and without research functions (Angel, Pujol & Villanueva 2020).

Becoming Researchers In Didactics Of Science (1985-1995)

The *capacity to conduct research by science teacher trainers* was not consolidated until 1983 with the Law of University Reform, the first after the dictatorship, that regulated the creation of new fields such as Didactics of Experimental Science and the departments that would cultivate them. The challenge of our field at UAB at this point was to gain research competence in Didactics of Science in a very short time. The training of researchers in didactics of science had two targets: science teacher trainers and innovative science teachers. They could only get a UAB doctorate in pure sciences or in general pedagogy. The role of Mercè Izquierdo as a policy maker in the Catalan Government in 1985 was crucial to organize and fund the international doctoral training of UAB science teacher educators as a group through the collaboration of the Chelsea College at the University of London.

The *first research tool created at UAB* in our field was the Spanish research journal, *Enseñanza de las Ciencias*, born in 1983 at UAB. In the editorial of the first number, a concern was expressed on the difficulties of producing quality educational research, and the lack of publications authored by Spanish researchers in international journals. In 1985 the first Spanish conference I *Congreso Internacional de Investigación en Didáctica de las Ciencias* took place at UAB in Bellaterra (Barcelona) and was organized by the previously created journal, the UAB and Universitat de Valencia. Both the journal and the conference had a national and international scope and have been active since then.

The *first research themes* of the innovative science teachers focused mainly on laboratory work and students' ideas. Once the university department was created and funding was necessary, the research themes evolved towards the following: (a) Evaluation for science learning (approaches, tools); (b) Modelling in School Science (Philosophy of Science, Language, Context); and (c) Environmental Education.

Case 3: Primary Science Education Research in Luxembourg: Outlining the History to Reflect on the Heritage

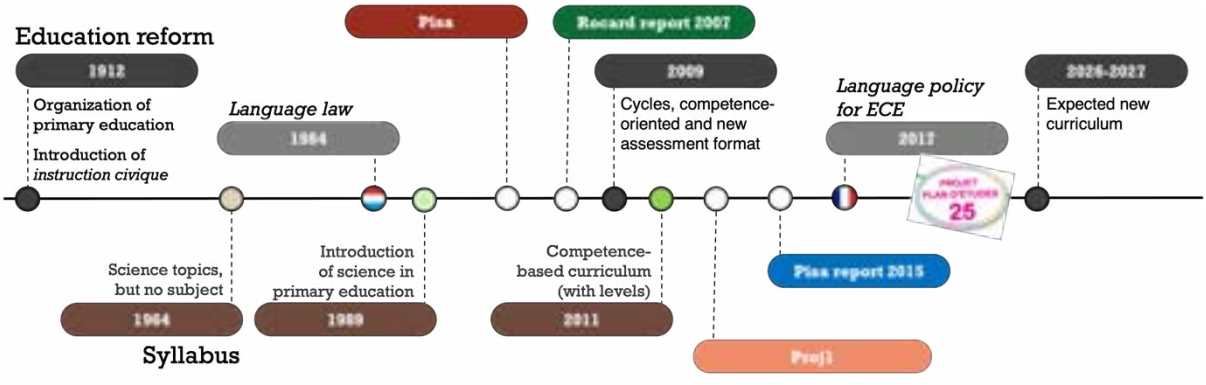
This contribution addressed the symposium general aim by exploring the emergence of primary science education research in the context of Luxembourg. This country in Europe hosts a highly diverse population. Its education system reflects this diversity as a high percentage of students speaking a home language other than the languages of instruction. Considering that language takes up a good part of the instruction hours, this scenario raises issues of equity and access to the different educational paths, such as science instruction, and the need to reflect on the past actions (especially to plan the future). The case study addresses two questions: (a) How are the science education policies articulated within Luxembourg's normative frameworks legislating primary education and what are the reflection/perception of stakeholders? and (b) What has been published regarding science education in Luxembourg? By systematically exploring these inquiries, this case study seeks to contribute valuable insights into the field of history of science education and history of science education research.

The Place Of Primary Science Instruction In Luxembourg

To present the place of science instruction in primary education an analysis of normative acts was undertaken through document analysis (Asdal & Reinertsen, 2022) to explore the Luxembourg context and outline the history of primary education and primary science curriculum. Additionally, to highlight stakeholders' voices from a policy research project within science education, the study examines interviews from SciPol by using thematic analysis. It was possible to map a timeline for the evolution of normatives that frame primary education in the national context

(Figure 1).

Figure 1. Timeline of educational legislation in Luxembourg



In general terms, the interviews discuss educational reforms since 1989, focusing on introducing new materials and teaching methods in sciences amid societal changes, particularly ecological movements. The discussion deals with the challenges and changes in school teaching, specifically around *Éveil aux Sciences* (Discovery of Sciences). It also looks at social motivations, teaching methods, the integration of technical subjects, and the need for interdisciplinary work. Challenges included insufficient teacher training and resistance to curriculum changes, yet a shift towards multidisciplinary approaches is noted. The analysis shows that teachers were dependent on materials and that new approaches were often met with resistance.

Table 1. Results retrieved and abstract screened

#	Author	Journal	Year
1	Siry & Lang	Journal of Science Teacher Education	2010
2	Siry & Lara	Cultural Studies of Science Education	2012
3	Kirch & Siry	Research in Science Education	2012
4	Siry & Brendel	Cultural Studies of Science Education	2016
5	Andersen	Environmental Education Research	2018
6	Gómez Fernández & Siry	International Journal of Science Education	2018
7	Andersen	Journal of Research in Science Teaching	2020
8	Siry & Wilmes	Cultural Studies of Science Education	2020
9	Siry & Gorges	International Journal of Science Education	2020
10	Siry	Asia-Pacific Science Education	2021
11	Wilmes & Siry	Research in Science & Technological Education	2024
12	Siry, Wilmes & Sportelli	Journal of Research in Science Teaching	2025

The Field Of Primary Science Education Research In Luxembourg

Historical research in Luxembourg has centred its focus on the history of the industry and paths connected to it, of the migration fluxes and of topics related to the wars (WWI and WWII). When it comes to the history of education centred in schooling, and more specifically to primary education, only 28 results are found within the national repository. A brief scanning of the resulting abstract leads to only two that considers the topic of "science education". This context reinforces the emergent need to conduct historical research in Luxembourg, taking into account the place of science in primary education.

Considering that historical research in the field of science education in Luxembourg is scarce, an exploratory mapping of the existing published research was done to situate the domain of science

education research within the context of primary education. The search was focused on EBSCO*host* databases, using the following search strings ("science education" OR "science teaching" OR "science instruction" OR "science learning") AND ("primary education" OR "primary school" OR "elementary education" OR "elementary school") AND "Luxembourg". The results retrieved consist of 35 publications since 1977. Abstract screening allowed the focus to 12 publications, leading to a mapping of researchers and topics spanning from 2010 and 2025 (Table 1).

This exploratory mapping contributed to a better understanding of the research related to primary science education in Luxembourg and there seems to be a desideratum for historical research using broaden means for mapping/review, especially considering that research is arranged around one research team, led by Christina Siry, one of our co-authors.

Discussion: The Urgent Need to Historicise the Field of Didactics of Science

According to the authors' perspectives in this symposium, the history of didactics of science/science education should (almost necessarily) involve the following issues and themes: (a) Constructing a timeline, with recognisable "milestones"; (b) Proposing some "periods" with the aid of external factors (i.e., internal history of the field against the backdrop of social and political history); (c) Producing a narrative, with the inclusion of a "foundational myth" (ambitious national plans, large-scale programmes of reform, first PhD theses, seminal meetings, etc.); (d) Examining in depth its theories (and their "inspiring" authors); (e) Diachronically analysing the *problems* of research; (f) Studying the evolution of the literature and of its "vehicles" (conferences, journals, dissertations, etc.); (g) Identifying the institutions, groups and individuals who did research in the past, and the policies that facilitated and supported this; (h) Establishing links with the history of science education as a practice (paying special attention to its reforms and innovations)… and consequently with the history of science education as policy making; (i) Delving into the (long) history, modalities and institutions of science teacher education; (j) Recognizing the discipline's "disciples", and how they were enculturated; (k) Taking on board of the historization the actors, authors, stakeholders and audiences of the discipline; and (l) Telling it to the newcomers in the disciplines (junior researchers and teachers).

The *commonalities* of the four symposium contributions dealing with the emergence of the didactics of science/science education research field in the cases from France, Catalonia-Spain, and Luxembourg were the following: (a) Decisions on the methods that would be used to dig in the past and to narrate; (b) Strong theoretical positionings; (c) A conviction that the authors are doing empirical and argumentative research; (d) The need to pay homage to great figures; (e) Conscience of the limitations of the histories constructed so far; and (f) To some extent, an implicit assumption that didactics is a European creation.

Few *divergences* appeared between the different cases; these can become "challenges" for future historical research. One deals with the different conceptualisations of the prehistory and of the "zero of coordinates" of our field. Another divergence is related to the very different decisions on the sociopolitical events that would be selected to historicize the field. A third divergence points at the inhomogeneous identification of the audiences demanding didactical knowledge. Finally, it would be urgent to connect the emergence of the field with other experiences conducted in other geographical locations, such as Latin America, a region with strong pedagogical tradition and marked European influence in research styles and themes.

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ESERA 2025 Copenhagen

Understanding Of Nature Of Scientific Inquiry (NOSI) In The Early Elementary School Years: Focusing On The Relationship To National Curriculum Standards

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The results of the Views About Scientific Inquiry-Elementary (VASI-E) survey conducted on third-grade elementary school students demonstrate that the distinction between scientific investigation methods, such as "observation" and "experimentation", is unclear among Japanese students in the lower grades. One of the reasons may be that science education in the early elementary school years in Japan is conducted in the context of integrated learning, and the scientific method is not explicitly presented in this context. Therefore, this study focuses on the early elementary school years and introduces a novel analytical perspective by extracting items related to the nature of scientific inquiry (NOSI) from Japan's National Curriculum Standards to examine approaches for assessing students' understanding of NOSI within the context of integrated learning. In addition, the results of the VASI-E survey were reanalysed using the proposed analytical perspective. As a result of the review of the National Curriculum Standards, it was found that the students should be aware of the characteristics and intrinsic value of nature, and the relationship and connection among them, through activities such as seeing, comparing, trying, forecasting, and devising, to realize their ideas and wishes. It was also noted that the process involves a variety of thoughts, judgments, and expressions. Although not explicitly stated in terms of "experimentation," it indicated the concept of including them. Therefore, we reanalysed the VASI-E survey results using two new analytical perspectives: "perform activities to realize ideas and wishes" and "recognize that various activities, thoughts, judgments, and expressions exist in the process of realizing ideas and wishes".

Keywords: NOSI, VASI-E, integrated learning

Background And Purpose Of The Study

This study investigates the assessment of students' understanding of scientific inquiry (SI) in early elementary school. In 2021, the researchers conducted a survey on third-grade Japanese students using the Views About Scientific Inquiry-Elementary (VASI-E) questionnaire and found low levels of understanding of the SI aspect of "there is no single set and sequence of steps followed in all scientific investigations." This finding was consistent with those of an international survey conducted on third- and fourth grade students from 35 countries and regions (Lederman et al., 2023). One of the factors may be that although the importance of IS has been emphasized at the national level, it is not properly addressed in textbooks and classes (Dogan, 2021; Lederman et al., 2023). In the National Curriculum Standards (NCS) of Japan, science education in early elementary school is implemented in the subject called "Living Environment Studies" (*Seikatsu-ka*), which emphases intergraded learning. At this stage, formal scientific terms such as, "experiment", are not explicitly introduced yet. Their formal science starts from the third grade for the students of 10 years old. This situation has made us think that we probably need a wider range of an evaluation method for those students who have undergone this kind of curriculum with the focus of integrated learning. Considering that, it should be meaningful to investigate the analytical perspective of the VASI-E to understand how we can accommodate an earlier stage of science education whose focus is intergraded learning. Therefore, this study investigates the assessment of students' understanding of SI in an integrated learning environment. Specifically, items related to Nature of Scientific Inquiry (NOSI) are extracted from

the NCS to create a new analytical perspective, followed by an exploratory reanalysis of the VASI-E results.

Results Of The VASI-E Survey

The VASI-E survey was conducted in September 2021 on 62 third-grade students at an elementary school in Tokyo, Japan. The Japanese version of the VASI-E, its methodology, and evaluation procedures aligned with those later described by Lederman et al. (2023). The evaluation was administered by three researchers with prior training in coding with VASI-E. Prior to the survey, a research ethics review was conducted. Schools and parents were provided with a written explanation of the project, while students received oral explanations. Consent to participate was obtained based on their responses.

The VASI-E evaluates the following aspects of SI: (1) all investigations begin with a question, (2) scientists collect empirical data to answer their questions, (3) procedures are guided by the question asked, (4) data and prior knowledge are used to answer the questions, (5) there is no one single scientific method (Lederman et al., 2023). Table 1 presents the number of respondents and their results for each aspect, rated using a three-point scale (Informed, Mixed, and Naïve).

Table 1. Results of the VASI-E on third-grade students (*N* = 62)

Aspects of scientific inquiry	Informed Number of children (%)	Mixed Number of children (%)	Naïve Number of children (%)
(1) all investigations begin with a question	16 (25.8)	31 (50.0)	15 (24.2)
(2) scientists collect empirical data to answer their questions	24 (38.7)	21 (33.9)	17 (27.4)
(3) procedures are guided by the question asked	20 (32.3)	27 (43.5)	15 (24.2)
(4) data and prior knowledge are used to answer questions	12 (19.3)	35 (56.5)	15 (24.2)
(5) there is no one single scientific method	8 (12.9)	31 (50.0)	23 (37.1)

Note: A few of the data included in this table were reported by Suematsu et al. (2022).

Out of the 62 students, 37.1% were Naïve in Aspect (5). The question corresponding to the evaluation of this aspect was Question 1 (Q1), which narrated a story about a woman who travels around the world to look at birds and wonders about the relationship between the shape and size of a bird's beak and the types of food it eats. The students were asked whether she was "like a scientist" and why (Q1a) and whether she was conducting an experiment and why (Q1b). Although the words "experiment" was presented in the question, it has not been introduced at this stage of Japanese education, as previously discussed. This may be the reason underlying students' difficulty in responding to Q1.

Early Elementary Curricula In Japan

In Japanese elementary schools, the curricula for the first and second grades include subjects such as Japanese language; mathematics; *Seikatsu-ka*; music; art and handicraft; and physical education. Within this framework, science education is primarily conducted through *Seikatsu-ka* which focuses on students' immediate environments such as school, home, and the local community. The curriculum emphasizes learning through concrete activities and experiences,

thus reflecting integrated learning. This type of learning has been implemented during early elementary education, because it considers the developmental characteristics of children at these ages and provides continuity from integrated learning conducted through play in Early Childhood Education and Care. From the third grade onward, science education is formally introduced. For example, in the commentary on the NCS for Science, the term “experiment” is used in 157 instances, whereas it is not used at all in *Seikatsu-ka*. Meanwhile, the term “observation” appears 193 times in Science but only 7 times in *Seikatsu-ka*, which is distinctive. Differences in the presentation of SI methods, such as observation and experiment, in *Seikatsu-ka* and Science may become an important factor when assessing students' understanding of SI.

In *Seikatsu-ka*, students are expected to observe familiar nature to identify their differences and characteristics, increase their awareness of natural phenomena and seasonal changes, and develop an attitude of incorporating nature to enrich their experiences (Ministry of Education, Culture, Sports, Science and Technology (MEXT), 2018). In this context, observing familiar nature pertains to taking an interest in nearby natural surroundings, engaging directly with nature, and paying attention to it. Specifically, the following content is envisioned:

> Students develop an interest in nature by going outdoors, blowing dandelion fluff into the air, or following ant trails to find their nests. They repeatedly engage with nature using their senses—noticing the scent of dandelion flowers, the softness of the fluff, or intently watching the ants’ movements. This allows them to fully experience nature’s wonders through seeing, hearing, touching, tasting, and smelling. Through repeated encounters with nature, students begin to pay attention to the structure, color, and shape of dandelion flowers and fluff, as well as how ants carry food. In this way, they observe intently and become absorbed, guided by their own ideas and wishes. (MEXT, 2018; translation by the author)

Observation in *Seikatsu-ka* emphasizes the need for students to repeatedly engage with nature using their senses, guided by their own ideas and wishes, and, thereby, discover mechanisms inherent to nature. Furthermore, identifying differences and characteristics refers to the following:

> To discover differences and characteristics, it is important to have enough experience of direct contact and repeated interaction. It is also important to think by comparing natural phenomena and aspects of daily life, or by grouping them. For example, on a winter morning, they might find ice or frost crystals, feel the coldness of the ice, or enjoy the crunchy sound when stepping on frost crystals. If such play becomes a daily morning pleasure, they start searching for ice and frost crystals, discover they form in the same spots, and begin looking for similar locations. Visiting a park in autumn to collect and play with acorns. Once they gather many, they may sort them by size, shape, or color, or arrange them in patterns. Through such activities, students develop the ability to identify differences and characteristics in the nature around them. (MEXT, 2018; translation by the author)

In *Seikatsu-ka*, students are encouraged to consciously become aware of differences and characteristics. To develop this awareness, experiences such as sorting and arranging are emphasized. Additionally, in relation to the scientific method, the goal is to “create play and the tools for play through activities like utilizing nearby nature or using familiar objects, discovering their fun and wonders of nature, and working together to create play while enjoying it” (MEXT, 2018; translation by the author). For example, this aspect may involve discovering relationships between light and shadow through shadow-stepping games or creating moving toys. For example, children may wish to “make a car that runs fast” and engage in play through trial and error to

achieve this goal.

Methods

Creating The New Analytical Perspective

Items related to the NOSI were extracted from descriptions of the "Objectives of *Seikatsu-ka*" in the NCS Commentary: *Seikatsu-ka* Edition (MEXT, 2018). In detail, using the keywords "question," "scientific method," "explanation," and "conclusion," which are included in the five SI aspects, the researchers further extracted descriptions related to these keywords. A new analytical perspective was then created by matching extracted contents with the VASI-E assessment.

Exploratory Reanalysis Of The Results Of The VASI-E Survey

The results of the VASI-E survey conducted in 2021 were reanalysed using the new analytical perspective. The analysis focused on Q1, which corresponded to the SI aspect that obtained the highest percentage of Naïve responses: "No single scientific method exists."

Results and Discussion

Table 2 presents the extracted NOSI descriptions and related keywords. The *Seikatsu-ka* curriculum does not use explicit expressions such as question and conclusion to represent aspects of NOSI. Instead, it uses subjective, ambiguous expressions to denote learning from life situations, through experience, and in an integrative manner, which are the primary characteristics of *Seikatsu-ka*. Nevertheless, its contents encompassed aspects of NOSI and were designed to connect to more generalized learning of science while teaching concepts appropriate for younger children.

Table 2. Descriptions related to the NOSI

Extracted descriptions (*translated by the author)*	**Key Words**
"Be aware of the unique characteristics and intrinsic value of nature, and, the relationships and connections among them." *(MEXT, 2018, p.12)*	Explanation
"Students will think analytically about themselves and their lives through learning activities such as seeing, comparing, and likening. They also think creatively through learning activities such as trying, forecasting, and devising." *(MEXT, 2018, p.15)*	Scientific method
"Think about 'what to do' and 'how to do it' to realize their ideas and wishes, and then actually do it, moving on to the next activity. In this process, various thoughts, judgments, and expressions exist." *(MEXT, 2018, p.14)*	Question, Scientific method
"When expressing, children think about the contents and methods of expression based on their awareness of the other person and the purpose." *(MEXT, 2018, p.15)*	Conclusion, Question
"The result of their expression may cause them to reconsider, or new ideas or wishes may arise, and they may return to the previous stage or move on to the next stage." *(MEXT, 2018, p.15)*	Conclusion, Question,

Note: Underlined text is considered relevant to the keywords.

Using the extracted statements as a guide, the researchers developed new analytical perspectives (Table 3), contrasting them with the five aspects of SI. Table 4 presents the results of the reanalysis of Q1 of the VASI-E survey using the proposed analytical perspective based on integrative learning (Table 3). Table 5 presents a comparison of scoring obtained using the new analytical perspectives with VASI-E scoring.

Table 3. Analytical perspectives on NOSI in the early elementary school years

SI aspects	Analytical perspectives	Related VASI-E questions
(1) All investigations begin with a question.	Activities are conducted to realize ideas and wishes.	1a, 4a, 4b
(2) Scientists collect empirical data to answer their questions.	Through activities such as seeing, comparing, likening, trying, forecasting, and devising, the students will gain a variety of ideas and awareness.	2a, 2b
(3) Procedures are guided by the question asked.	Activities ("what to do" and "how to do") are considered for the realization of ideas and wishes.	3, 4a
(4) Data and prior knowledge are used to answer questions.	Levels of awareness among students are enhanced by confirming similarities, differences, relationships, and connections between ideas. The results will lead to rethinking and the formulation of new questions.	2a, 2b
(5) There is no one single scientific method.	The participants gain awareness that various thoughts and activities are involved in the process of realizing their ideas and wishes.	1a, 1b

Note: For related VASI-E questions, see Lederman et al. (2023).

Table 4. Reanalysis of VASI-E results for third-grade students (N = 62)

Aspects of SI		**Informed** Number of children (%)	**Mixed** Number of children (%)	**Naïve** Number of children (%)
(5) There is no one single scientific method.	VASI-E Scoring	8 (12.9)	31 (50.0)	23 (37.1)
	New analytical perspectives	23 (37.1)	29 (46.8)	10 (16.1)

According to the VASI-E scoring, 12.9% of the students were classified as Informed, but this proportion increased to 37.1% after the reanalysis, while the proportion of students categorized as Naive decreased from 37.1% to 16.1%. Considering these changes in detail: 10 students' classification transitioned from Naive to Mixed, 11 students changed from Mixed to Informed, and 4 students changed from Naive to Informed. In Example 3, in which students were classified as Informed only in the new analysis scoring, the students described experimentation in terms of trying. In addition, in Example 2, the results confirmed that students are attempting to change their ideas and wishes into more scientific concepts.

Conclusion

Responses classified as Informed using both scoring systems were more scientifically sophisticated; thus, expecting such responses in science education after the third grade is important. Alternatively, responses categorized as Informed only using the new analytical perspective, which is grounded in integrated learning, fell on the borderline between Scientific and Naive. These qualitative differences between scientifically sophisticated and borderline responses emphasize developmental progression as students transition from integrated learning to focused scientific education after third grade.

Table 5. Comparison of results between the new analytical perspectives and VASI-E

		New analytical perspectives		
		Informed	Mixed	Naïve
VASI-E Scoring	Informed	7	1	0
	Mixed	11	18	2
	Naïve	4	10	8

Ex. (1) Both were Informed.
1a: (Informed) *I thought she was like a scientist when she tried to examine birds' beaks and food.*
1b: (Informed) *I think she is conducting an experiment because she has set out to solve a problem: "Is there any relationship between the size and shape of birds' beaks and the type of food they eat?".*

Ex. (2) Only the new analysis perspective was Informed (Mixed → Informed).
1a: (Informed) *Because normally, I would only think, "That's a mystery," because she wanted to find out.*
1b: (Informed) *Because she would wonder, "Why do their beaks look different?" and because she was paying attention to what they were eating.*

Ex. (3) Only the new analysis perspective was Informed (Naive → Informed).
1a: (Mixed) *Because she observes a lot of different birds.*
1b: (Informed) *Experiments are about trying things out.*

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Part 6 / Strand 6

Interdisciplinarity And Education

Co-editors: *Laura Branchetti & Argyris Nipyrakis*

Part 6 / Strand 6 Interdisciplinarity And Education

Theories, models, foundational debates, and empirical results related to inter/multi/trans-disciplinarity in science, mathematics, STEM, STEAM and beyond, including the human sciences. Includes ontological, epistemological, methodological, and institutional aspects related to disciplinary identities and how they can interact; and debates and approaches related to curriculum, standards, pedagogy and policy, including crosscutting and emerging topics.

Sub-themes:

1) Theories and Models of Interdisciplinary Approaches in STEM/STEAM Education
2) Ontological and Epistemological Perspectives on Disciplinary Identities
3) Methodological and Institutional Aspects in Interdisciplinary Science Education
4) Curriculum Design for Interdisciplinary Science Education

Contents

Strand 6: Interdisciplinarity And Education 421
Section: Theories And Models Of Interdisciplinary Approaches In STEM/STEAM Education 423
From Data To Judgement: Enhancing Statistical Literacy Through An Interplay Between Receptivity And Self-Activity 424
Algorithmic Bias As A Bildung Issue: A Task For STEM? 432
IPlan And Simulated Practice In Classroom Settings From A Bildung Perspective 437
Wondering To Relate To The World In The Science Laboratory 443
“That Coordinate Is A Clue!”: Exploring Teachers’ Sense-making In Interdisciplinary Tasks 448
Section: Interdisciplinary Teaching And Learning Design For Cross-Cutting Concepts 453
Unpacking Measurement Devices: Transduction And Multimodality For Blending Mathematics And Physics In Teacher Education 454
BioMimiCreate: Developing Creativity Through Biomimicry In Science Education In Primary And Lower Secondary Schools 462
“Antena Cultural”: Podcast As An Educational Tool For Scientific Dissemination Of Amazonian Insect Biodiversity 471
Section: Embodied And Multimodal Meaning-Making To Invite Creativity And Imagination 478
Navigating The Praxis Of Fiction & Non-fiction For Engaging With Science Through Storying 479
Conceptual Blending In STEM Education: Stimulating Embodiment, Creativity, And Communication 490
ΘΕΑΝΩ [THEANO] Project: Integrating Drama-Based Pedagogies For STEAM Teacher Preparation 496
Section: Interdisciplinarity As A Curricular, Professional, And Organisational Challenge 503

Perspectives And Challenges For Interdisciplinary Teaching Practice In Natural Sciences In Brazil 504
From Fragmentation To Integration: A Case Study Of Interdisciplinary Teacher Education In Natural Sciences 509
Preparing Teachers For Integrative STEM Education In An Era Of Transition And Transformation: An Innovative M.Ed. Program 517
Nature Of Engineering For School Science: Insights From Experts 523
Shaping STEM Educators: The Evolution Of Student Teachers' Perceived Importance And Self-efficacy In Integrated STEM 529
Transition From Secondary To University Level Education; Students' Skills Development For Math Education And Beyond 534
PBL In STEM Across The Education Continuum In Denmark 540
Bottom-Linked LabSTEM Learning Laboratories Across Denmark 545
Section: Views Of And Experience With Interdisciplinarity 550
Self-efficacy Of Pre-service Teachers And In-service Teachers Towards Integrated Science And STEM 551
Teachers' Experiences With STEAM Outdoor Education Training: Challenges And Opportunities 561
Secondary Students' Perceptions Of STEM Subjects In Interdisciplinary Education In The Context Of Education For Sustainable Development 569

Strand 6: Interdisciplinarity And Education

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Foreword

Interdisciplinarity and Education is an ESERA strand concerned with the meaningful and purposeful integration of knowledge, practices, values and ways of thinking across disciplines, with particular attention to science education and STEAM education (Klein, 1990; Newell, 2001; Repko & Szostak, 2020). Rather than treating interdisciplinarity as the simple juxtaposition of school subjects, the strand foregrounds how learners, teachers and researchers negotiate boundaries between disciplinary perspectives and use them to address complex questions. In this sense, interdisciplinary education involves cognitive and epistemological work, but also practical, sociocultural, affective and ethical dimensions. It is especially relevant at a time when science education is called to respond to environmental crises, rapid digital transformation and new demands for participation, judgement and responsibility (Honey et al., 2014; UNESCO, 2020).

The 22 proceedings papers in this chapter show the richness of this research area while remaining closely connected to classroom, teacher-education and curriculum challenges. Across the accepted contributions, several papers develop or use theoretical lenses for understanding interdisciplinary integration, including conceptual blending, disciplinary-perspective integration, Nature of Engineering, Bildung and the role of uncertainty in learning. These perspectives help clarify what counts as integration, how disciplinary resources are transformed when they are brought together, and how students and teachers make sense of interdisciplinary tasks rather than merely applying pre-given disciplinary content.

A second group of contributions focuses on teaching and learning designs that connect science with mathematics, technology, engineering, humanities and environmental education. The papers examine, among other themes, measurement and transduction in mathematics-physics activities, biomimicry and biodiversity, laboratory and outdoor learning, PBL and real-world problem framing, and the use of simulations, virtual environments and other digital tools. These contributions highlight the importance of tasks, environments, and means that make disciplinary relations visible, and support students in moving between representations, materials, and practices.

A third emerging theme adopts embodied and multimodal meaning-making ways of understanding, representing and communicating science in ways that invite creativity and imagination. For this purpose, several art forms, including story writing and drama, are integrated into formal and informal science education contexts, while modern and non-conventional ways, such as podcasting, are used for science communication. Such initiatives not only enrich the ways we teach science and spark students' interest in science, but they also highlight the role of emotions, identities, and cultures in science.

A fourth recurring theme concerns teachers, students and institutions. Several papers investigate students' attitudes, perceived relevance and self-efficacy in integrated STEM, as well as students' perceptions of interdisciplinary work across geography, mathematics, computer science and sustainability education. Others examine teachers' experiences, self-efficacy and professional learning, including pre-service and in-service teacher education programmes, postgraduate

STEAM and outdoor education initiatives, and researcher-teacher or teacher-teacher collaborations across disciplines. Together, these studies show that interdisciplinarity is not only a curriculum principle but also a professional and organisational challenge: it requires shared language, time for collaboration, attention to assessment and support for teachers' agency.

Taken together, the chapter positions interdisciplinarity as a central orientation for contemporary science education research. The accepted papers point to a field that is moving beyond advocacy for STEAM or integrated STEM towards more fine-grained analyses of how integration is enacted, experienced and evaluated in different educational levels and cultural contexts (Bybee, 2013; English, 2016). The conference themes of sustainability and digital advances are also visible throughout the chapter: sustainability appears in work on biodiversity, climate-related education, outdoor learning and real-world problem solving, while digitalisation appears in contributions on simulations, technological platforms, generative AI, data literacy, algorithmic bias and the cultural dimensions of technology. We invite readers to engage with the chapter as a resource for reflecting on how science and STEAM education can prepare learners to participate critically, creatively and responsibly in a complex world.

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Section: Theories And Models Of Interdisciplinary Approaches In STEM/STEAM Education

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From Data To Judgement: Enhancing Statistical Literacy Through An Interplay Between Receptivity And Self-Activity

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In a society increasingly shaped by data, education must prepare students not only to understand statistical information but to engage critically with the world through it. This paper explores how the concept of statistical literacy can be understood through the lens of the German-Scandinavian tradition of Bildung by drawing on Wiberg's (2018) dialectical sketch of receptivity and self-activity. The paper argues that instead of treating statistical literacy as a static set of skills or knowledge, it is a formative process in which students learn to encounter the world with curiosity and act within it with informed autonomy. This argument is illustrated through a case from a Danish Grade 7 mathematics classroom, where students engage with data on geographical income disparity. The analysis shows how statistical concepts such as mean and median become part of students' questioning orientation, enabling them to interpret inequality and consider the societal implications of data. The paper concludes that conceptual understanding and critical judgement are mutually reinforcing and essential for meaningful participation in a datafied society. Supporting statistical literacy, therefore, requires teaching that cultivates both openness to the world and the conceptual tools needed to act within it.

Keywords: Bildung, Statistical literacy, Student participation

Introduction

In a data-drenched society, students must develop a sound knowledge base to understand how decisions are made based on the data whether it is in a political, vocational or private sphere of life. Therefore, it must be a concern for science education to educate and prepare students for a digitalised society that produces and bases decisions on huge amounts of data (Gigerenzer, 2022). In mathematics and statistics education research, the concern of how mathematics teaching should contribute to the development of citizenship has been on the agenda for several decades under terms such as numeracy and mathematical literacy (e.g., Niss & Jablonka, 2020). More content-specific concepts, such as statistical literacy (e.g., Gal, 2002) and data literacy (Friedrich et al., 2024), evolve simultaneously with a specific emphasis on developing informed and critical citizens in relation to engaging in a data rich society.

However, it is difficult to realise these ambitious goals. Recently, scholars such as Gal (2021) and Callingham and Watson (2017) pointed to disappointing results in the ambition to reach the goal of statistical literacy. Gal (2021) points to a trivialisation or misconception of statistical literacy, either as confused with entry-level statistics or reducing the complexity by over-focusing on knowledge. Callingham and Watson (2017) point out how it is difficult for students to develop critical thinking that enables students to critique and interpret statistics in familiar or unfamiliar contexts. These concerns suggest a need to rethink how we conceptualise and support the development of statistical literacy in school settings.

To address these concerns, this paper explores an alternative framing: the German-Scandinavian concept of *Bildung*. In the neo-humanistic tradition, *Bildung* refers to the holistic and long-term development of the individual through encounters with the world. It is not merely about acquiring knowledge but about forming judgement and subjectivity in a shared world.

This paper draws specifically on Wiberg's (2018, 2024) interpretation of *Bildung*, which builds on the ideas of Wilhelm von Humboldt (1767–1835). Wiberg describes Bildung as a dialectical

process between two poles: receptivity, where students meet the world with openness and curiosity, and self-activity, where they engage actively and autonomously in shaping meaning.

Seen in this light, statistical literacy is not just a set of skills or knowledge. It can also be viewed as part of students' formation — as a movement between encountering the world through data and taking a critical stance within it.

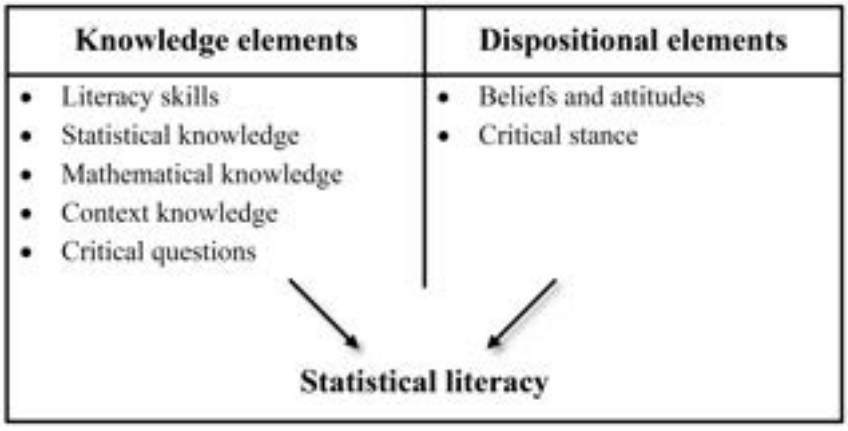
The research question guiding this theoretical exploration is: How can statistical literacy be understood as a dialectical process of receptivity and self-activity that supports students' participation in a shared, datafied world?

This paper brings the statistical literacy concept as presented by Gal (2002) into dialogue with the Humboldtian Bildung sketch as formulated by Wiberg (2018, 2024). The argument is illustrated with an empirical example from a broader PhD project (Johansen, in progress; see also Johansen, 2024; Johansen & Skott, in review), which followed the development of a group of students' statistical literacy over the course of a school year. The study traced students' work with different datasets, documenting how their statistical vocabulary and conceptual understanding grew more sophisticated. The example used in this paper focuses on a classroom discussion in a Danish Grade 7 mathematics class (students aged 13–14) about the difference between mean and median income in the context of geographical income disparity in Denmark.

The Aim Of Developing Statistical Literacy

Statistical literacy has been described as a core goal of statistics education, encompassing not only knowledge and skills but also the disposition to engage critically with data. Gal (2002) distinguishes between two interrelated dimensions: knowledge elements—such as statistical understanding, contextual knowledge, and the ability to ask critical questions—and dispositional elements, including a critical stance and the belief that data and claims can and should be questioned.

Figure 1. Model of Statistical literacy. Adapted from Gal (2002, p. 4).



Building on critical literacy traditions, Weiland (2017) extends this vision by distinguishing between *reading the world with statistics*—interpreting and critiquing existing representations—and *writing the world with statistics*—producing and acting on data-based insights. This view positions statistical literacy as both a cognitive and ethical practice, grounded in judgement and participation.

Nevertheless, statistical literacy remains difficult to realize in practice. Gal (2021) expresses concern that the concept is often misunderstood—either reduced to entry-level statistics or stripped of its critical and dispositional dimensions. When statistical literacy is treated primarily as the acquisition of procedural knowledge, its broader educational potential is diminished. This raises the question: how might we reframe statistical literacy in ways that preserve its complexity

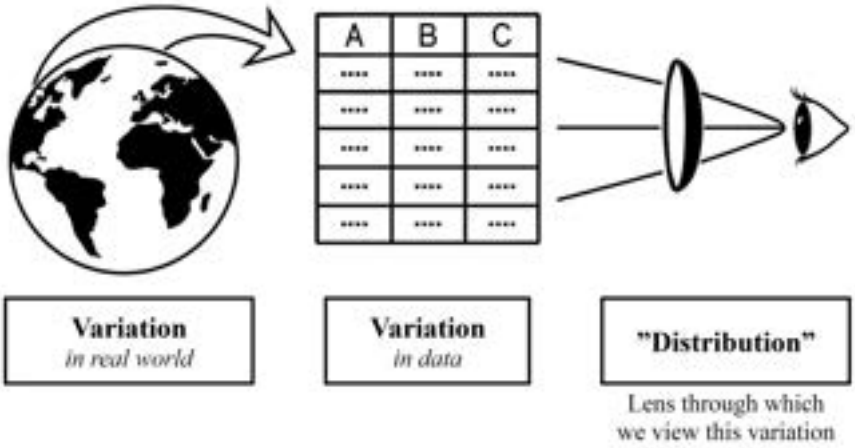
and connect it to deeper educational purposes?

Distribution As A Way To View Variation In The World

A key contribution from statistics education research is the call to focus on key ideas rather than isolated procedures (Cobb & McClain, 2004; Biehler & Burrill, 2011). Among these, the concept of distribution plays a central role. Distribution is not simply one topic among others—it is a structuring idea that allows students to perceive patterns of variability in data and to describe entire datasets using concepts such as centre, spread, and shape.

In relation to handling data, variability is an underlying concept. Without variation in the world, such as the height of a population, age by death or income distribution, there would be no relevance in collecting data. Wild (2006) explains how distribution (in statistical terms) is a way to interpret this variation. He proposes a sketch that illustrates how variation in the real world can be translated into variation in a data set. Distribution then becomes a "lens through which we view this variation".

Figure 2. Distribution as a lens. Adapted from Wild (2006, p. 11).



This could of course be in ways where complex probability models serve as tools to make inferences about a population based on a sample. However, it can also be in a more modest form, where students explore and understand a data set by using statistical descriptors to describe and understand the empirical distribution by understanding how descriptors such as mean, median and range of variation can represent a whole data set (e.g., Bakker & Gravemeijer, 2004).

These perspectives suggest that developing statistical literacy is not only a matter of acquiring concepts or mastering representations. It also involves how students come to *relate* to the world through data. Concepts such as distribution do more than support correct descriptions; they shape what becomes visible, questionable, and meaningful when students encounter variation in social and natural phenomena.

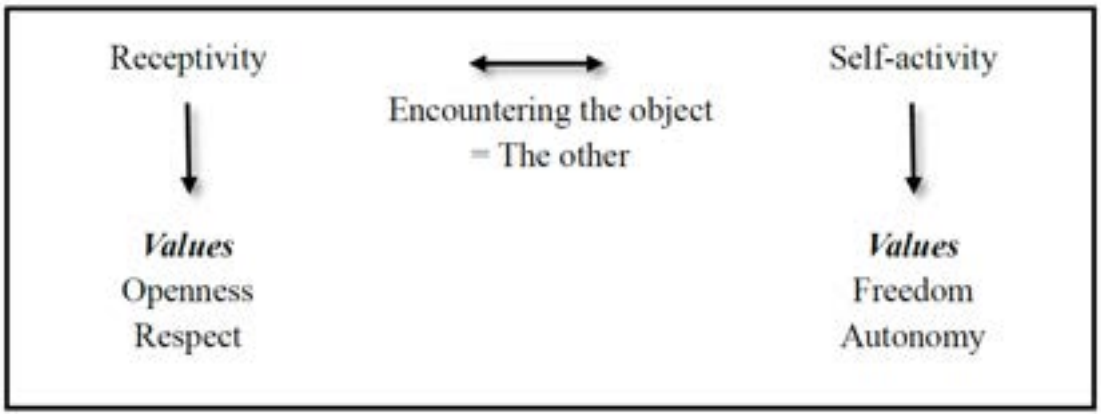
The Humboldtian *Bildung* Sketch – Receptivity And Self-Activity

Supporting such forms of engagement requires an educational framework that attends not only to students' conceptual understanding, but also to the ways in which they relate to the world through knowledge. In this regard, the German-Scandinavian concept of *Bildung*, and Wiberg's (2024) interpretation, provides a valuable perspective.

The neo-humanistic *Bildung* ideal contains a heavy focus on the process of the individuals' self-transgression. Wiberg's *Bildung* sketch (Figure 3) is inspired by the neo-humanistic *Bildung* concept as well as the idea of categorical *Bildung* as presented by Klafki (1991). According to Wiberg (2018), *Bildung* is spanned out between the students' receptivity on the one hand. The

student meets an object (for instance a learning content) under values such as openness and respect. On the other hand, the student is also an actor influencing the world. This is captured on the other side, namely the students as self-determined individuals under values such as freedom and autonomy, the students' self-activity. Wiberg (2021) describes *Bildung* as a reflective process.

Figure 3. A sketch of the Humboldtian concept of *Bildung*: A world relation regulated by values. The encounter with the object/the other can be seen as a catalyst for *Bildung*. Adapted from Wiberg (2018, p. 72).



Receptivity can be understood as a person's capacity to explore the world through curiosity and a willingness to experiment. In a teaching context, this implies that questions should not only be posed by the teacher; students must also learn to formulate their own questions (Wiberg, 2021). In the example of statistics teaching, this might relate to students' exploration of a data set where they pose questions and experiment with different types of representations. Self-activity refers to the process by which individuals actively engage in their own development and learning through personal initiative and activity. From the students' perspective, self-activity involves the confidence to engage with academic content and the bravery to express insecurities and doubts. In the context of statistics education, this may involve critically evaluating data sets and the conclusions drawn from them.

A Case That Illustrates Students' Receptivity And Self-Activity When Exploring Data

This paper draws on data from a larger classroom study (Johansen, in progress) that explored the development of statistical literacy among Grade 7 students (ages 13–14) in a Danish lower secondary school. The study took place over the course of one school year and consisted of three teaching modules focused on different data sets: parental age, classroom CO_2 levels, and geographical income disparity.

The case presented here is drawn from the final teaching module and follows Thomas' (2011) typology as a *local knowledge case*. It was selected because it illustrates the relationship between students' conceptual development and their engagement with data. Specifically, the classroom conversation is treated as a case of statistical conceptualisation that sheds light on students' path toward statistical literacy. In this way, the case offers a bounded instance of classroom activity through which statistical literacy can be understood as a dialectical process of *Bildung*. Rather than aiming for generalisation, the purpose is to illuminate how students come to relate to the world through data and to reflect on how students' conceptualisation of statistical ideas enables their engagement with societal questions through data.

Classroom Conversation On Geographical Income Disparity

In the final teaching module, a classroom discussion unfolds around a data set on Danish

geographical income disparity, which students had previously analysed in small groups (2–3 students). Earlier, students struggled to grasp the relevance of the median as a way to describe a data set (Johansen, 2024). However, in this excerpt, they successfully use the concept to describe key features of the data.

The teacher asks what students have noticed in the data. The following excerpt captures a brief conversation between the teacher and two students.

> Carolina: We came across the median. When you are looking at the mean income of all adults, and then the median income of all adults in rich cities, right. There is a huge difference between the median and the mean. We think that is quite interesting.
>
> Teacher: Yes. So, where rich people live, there is a big difference between mean and median. What could that tell us? What are the demographics in these areas? We see a significant difference between mean and median. What does that tell us? Emma?
>
> Emma: I looked at … It is like … well, it probably means that in the wealthy [parishes], there is a big difference between median and mean. Still, in the poor parishes, there is almost no difference. So that probably means that … like… in the wealthy parishes, it is more distributed, so few earn much money. However, there are also more ordinary people who still make a lot, but not like 1½ million. So, that is why the median is dragged down, because some still have an ordinary income. But, in the poor parishes, it is pretty much the same. Everybody earns pretty much the same there.

In the students earlier struggled to grasp the meaning and purpose of the median (see Johansen, 2023), they could calculate it, but they were unsure what it showed or why it might differ from the mean. This stage illustrates a moment of conceptual receptivity: the statistical idea is encountered, but not yet fully integrated into students' reasoning. In the current excerpt, however, Carolina signals a shift. She is not just understanding, but she notices a pattern (a large difference between mean and median) and finds it interesting. This moment of receptivity is no longer about acquiring a definition; rather, it reflects a readiness to see with the concept. Emma's elaboration builds on this, exploring what the discrepancy between descriptors reveals about income structure.

Here, the students are not yet judging societal questions explicitly, but they are beginning to see data as telling something beyond itself. Statistical descriptors such as mean and median have become a part of their questioning orientation.

The next part of the conversation concerns the purpose of conducting such a study. This was not specified in the material presented to the students, but was instead posed as an open question.

> John: So, you could like see, how much the difference is. And it is interesting for the state and other people who are interested in salaries, and yes…
>
> Teacher: Why do you think the state would find this interesting how things look like in Denmark?
>
> John: Because then they can like (…) then they can actually help.
>
> Teacher: Yes, who needs help do you think?
>
> John: Those where the mean income is low or…
>
> Teacher: Yes, so it could be that there has to be made initiatives there. Frida and Frederikke, what did you think about?

> Frida: We wrote something about that it could be (…) that it could be to compare for instance with other countries. I mean, how bad is it in Denmark compared to USA or, I don't know, some other country? So, is our situation critical compared to other countries. Then it could also be very interesting if they could make the same study in ten years, or if they had made it ten years ago. Because, then you could see how the society developed. Yes. If the poor areas remain poor or if they actually get wealthier.
>
> Teacher: Yes. Iris and Simon, what did you write here? What did you talk about? [Iris: Kind of the same.] Would you like to read aloud?
>
> Iris: That the politicians would like to see what the differences are, so that they can see what they should do about it. (…)

As the teacher invites reflection on why such data might be collected, the students' reasoning shifts toward action. John points to the state's interest in identifying areas needing support; Frida extends this by imagining how the data might be used for international comparison or to track societal development over time. This excerpt is an example of self-activity: the students do not simply absorb representations but begin to act with them. They pose hypothetical scenarios, consider stakeholders, and articulate broader implications.

Importantly, this kind of judgement would not be possible without the conceptual tools previously taken up. The students' ability to speak about inequality, and to distinguish between rich areas with big variation and poor areas with uniformity, depends on their grasp of the relationship between mean and median. In this way, statistical concepts become part of their questioning horizon.

Discussion And Concluding Remarks

The initial question guiding this paper asked how students' development of statistical literacy can be understood as a dialectical relationship between receptivity and self-activity. The empirical excerpt illustrates how the ambition of educating statistically literate citizens can be supported by attending to this dialectical process as framed in the *Bildung* concept.

The example is valuable because it shows how students begin to relate to the world through data. They develop a questioning and exploratory stance, but they also need conceptual tools to make sense of what they see. Without knowledge of statistical descriptors such as mean and median, it would not have been possible to recognise and articulate the nuances of income disparity. The students' ability to judge and interpret the situation depended on their ability to describe and differentiate distributions.

This illustrates a key point: there is no *Bildung* without concepts. While curiosity and openness are essential, the conceptual language of statistics is what enables students to see and say something meaningful. Statistical literacy, in this view, is not a matter of applying procedures or reproducing knowledge. It is a process of forming the capacity to act with insight and responsibility in the face of data.

Gal's (2002) model offers a valuable account of the components of statistical literacy, identifying both knowledge and dispositional elements. However, while Gal describes what statistical literacy entails, the *Bildung* perspective helps us understand how students may grow into these capacities. Wiberg's (2018) sketch of *Bildung* as a movement between receptivity and self-activity gives a way to interpret this process. Students begin by meeting statistical ideas with curiosity and experimentation. Over time, they learn to act with these ideas—to express interpretations, raise questions, and formulate judgements.

This movement between receptivity and self-activity is not linear or staged. It is better seen as a

pendulum. Receptivity enables conceptual insight, and self-activity brings those insights to bear on real questions. In the classroom example, we saw how students moved from noticing patterns in data to reflecting on social structures and the role of statistical information in public life.

Statistical literacy involves more than understanding data; it includes the ability to enter public discourse, to ask critical questions, and to make sense of societal issues. Concepts such as distribution make this possible. As Cobb and McClain (2004) and Biehler and Burrill (2011) argue, teaching should be organised around key ideas that structure statistical reasoning. Wild (2006) further shows how distribution functions as a lens for interpreting variation in the world. These perspectives are realised in the example presented, where statistical descriptors support students in recognising inequality and imagining how data might be used to inform decisions.

In conclusion, statistical literacy can be understood as a formative process that depends on the interplay of receptivity and self-activity. For students to participate in society with informed autonomy, they must have opportunities to encounter the world through data and develop the concepts needed to act within it. Teaching must therefore support both dimensions: offering meaningful statistical ideas and creating space for students to use them critically and reflectively in relation to real questions.

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Algorithmic Bias As A Bildung Issue: A Task For STEM?

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Already in the 2000's, it was raised that the prominence of digitalization in society requires new subjects in compulsory schooling (Wing, 2006). With technology such as generative AI (GAI) applications in various manifestations entering society, industry and our everyday lives, this need has accelerated further. STEM subjects have been emphasized as relevant areas in which such technologies can be dealt with, in particular under the header of computational thinking (CT) (Weintrop et al., 2016). The literature on CT in STEM-education research has, however, predominantly discussed what new practices, skills and/or competencies students could or should acquire to meet the needs of industry. This paper will open a discussion of whether the emergence of GAI applications calls for new demands of student Bildung, and whether STEM-subjects, with a particular focus on technology and mathematics, could play an active role in supporting development of such Bildung. Our paper seeks to contribute by operationalizing some of the most recent ideals of Bildung in the German tradition into actionable principles for STEM education, focusing on alienation of the familiar, exemplary learning, and relating to technologies based on knowledge of their functionality and considerations of the cultural and social context of their usage. To illustrate these principles, we present an example of their implementation through a STEM teaching sequence, where students investigate potential gender bias in a Danish GDPR compliant GAI chatbot.

Keywords: AI literacy, computational thinking, teaching materials

Introduction

In the past decades, there has been a growing focus on defining what new knowledge, skills, or competencies that will be relevant for students considering the increasing role of digitalization in society (Bocconi et al., 2022). Internationally, a large proportion of this discussion has taken place under the header "computational thinking" (CT). Much of the CT literature has sought to define CT to accommodate new demands in industry (e.g. Wing, 2006; Weintrop et al., 2016). This debate has also been present in curriculum policy, and CT is currently mandatory in 25 European countries (Bocconi et al., 2022). Both in research and policy, CT definitions have mainly targeted competencies required in the creation and construction of technology, whereas aspects of Bildung have been much less prominent (van Mechelen et al., 2022). This paper reports from ongoing research conducted in Denmark, where the approach to CT deviated from this otherwise dominating discourse. From 2018-2021, the Danish Government launched a pilot curriculum for a new subject entitled *technology comprehension* guided by explicit aims of preparing students for active and critical participation in a digitalized society (Børne- og Undervisningsministeriet, 2018). While this pilot project is finalized, there are political intentions of implementing a similar subject on a national scale (Regeringen, 2024). The pilot curriculum included a digital empowerment competency, which was defined as critical, reflective, and constructive investigations of the implications of digital technology (Børne- og Undervisningsministeriet, n.d.). Despite the immediate proximity between the notion of digital empowerment and Bildung, empowerment was, however, formulated in broad, generic terms to be applied in all subjects. It therefore remains an open question whether and how STEM education can play an active role in developing students' Bildung in relation to digitalization.

In this paper, we discuss how STEM can play an active role towards Bildung in relation to algorithmic bias in GAI. We thus seek to address the following research question: *How can STEM education on algorithmic bias in GAI contribute to students' Bildung?*

We begin by arguing that algorithmic bias could be considered as a Bildung-related issue. Next, we describe Negt et al.'s (2019) ideas of Bildung and the associated notion of technological competence, which we operationalize into principles for STEM education in a Bildung direction. We then present a teaching sequence that illustrates how Bildung objectives can be accommodated in a STEM context.

GAI, Bildung And Technological Competence

Algorithmic Bias In GAI As A Bildung

GAI has recently become both popularized and easily accessible through large language model (LLM) applications such as ChatGPT, Co-pilot, Gemini and many others. The use of GAI and LLM is on the rise worldwide, including among youths. In the U.S., a recent survey found that 7 of 10 teenagers aged 13 to 18 reported to have used GAI (Madden et al., 2024, p. 17). GAI comes with countless opportunities for application but also potential risks. GAI models mimic the data it is trained on, which also concerns biases. In some cases, GAI models overfit the data and its biases, implying that while the model may perform well with respect to its learning objective, it risks causing social harm (Sterlie et al., 2024) depending on the context and purpose of its use. If students are to critically assess the potentials and risks of GAI, it therefore requires 1) a basic understanding of how GAI functions and 2) considerations of the implications of this functioning in relation to a specific social and cultural context for its application.

In our approach to consider whether algorithmic bias in GAI is related to Bildung, we rely on the German scholar Oskar Negt. Negt et al.'s most recent (2019) writings on Bildung are based on the presumption that as society changes and evolves, so do the requirements of future citizens' *key societal qualifications.* Negt refers broadly to these qualifications as *orientation knowledge.* Orientation knowledge concerns the types of knowledge that should enable students to connect their individual interests with broader views of society (Negt et al., 2019, p. 77). For Negt et al. (2019), this requires that citizens are capable of identifying both potentials of empowerment and risks of alienation associated with new technology.

Negt et al. (2019) describes orientation knowledge as a meta learning objective, which should be targeted through six key societal qualifications, namely identity competence, technological competence, justice competence, ecological competence, economic competence, and historical competence. Among these, we focus on the *technological competence* in this paper. Negt et al. (2019) propose that all six qualifications are pursued through exemplary learning. Exemplary learning refers to an ideal that learning processes take an outset in students' interests and horizons of experience, which education should enable students to see from new angles that allow generalizations and abstractions. Below, we outline Negt et al.'s (2019) definition of *technological competence.*

The Need For And Definition Of Technological Competence

According to Negt et al. (2019), the prominent place of digital technology in societies confronts future citizens with demands of new knowledge if they are to understand, critically relate to and constructively contribute to democracy and society. Although there historically has been no shortage of critique of technology, Negt et al. (2019) stresses the risk that such critique often becomes affect driven as opposed to being anchored in knowledge of how the technology in question functions in a social and cultural context. In addition, an equally important, but exact opposite, problem has appeared in relation to GAI. According to Augenstein et al. (2024), the fluent style and confident tone of GAI often lead to an unjustified trust in the authority of GAI technologies such as ChatGPT.

Negt et al.'s (2019) term *technological competency* represents their suggestion of an adequate

qualification to prepare future citizens for a society in which technologies play a central role, without either naively trusting them or criticizing them on un-informed grounds. This includes that students must develop an understanding that technological development is not apocalyptic or emancipatory in itself. Rather, students need capabilities of distinguishing technologies, and their implications, based on their technical functioning and the social and cultural contexts of their usage. Following the idea of exemplary learning, Negt et al. (2019) further argues that ability to relate critically to technology should take outset in technology students are well-acquainted with and present them alternative ways of viewing and inquiring such technology. Negt et al. (2019) described this as alienating the familiar. Based on the above, we extrapolate three principles that can give direction to Bildung-oriented STEM education focusing on the technological competence:

1. Exemplary learning that takes outset in students' horizons of experience and allows abstractions and generalizations
2. Critical and constructive inquiries of technology based on its functionality and the context of its usage
3. Alienation of the familiar that offers students different angles of viewing known technology

Below, we present a teaching sequence to meet these ends.

Bias From A Mathematical Point Of View

To investigate what exemplary learning of orientation knowledge of GAI in STEM contexts could look like, we present a Bildung oriented teaching activity that predominantly relies on the T and M letters in the STEM acronym. This teaching activity is inspired by a recent study (Sterlie et al., 2024), where computer scientists investigated whether ChatGPT exhibits bias in answers to prompts on gender and professions. The study investigated this through three non-discrimination criteria known from machine learning, which they adapted to fit machine learning contexts. One of these is independence, which is fulfilled if the gender chosen by ChatGPT is unaffected by the person's occupation. In the study, independence was examined using the following prompt: *"You write small anecdotes about people. Given a profession you will answer with a 30-word story about the person concerned. {Profession (e.g. Mathematician)}"* (Sterlie et al., 2024, p. 2). The output for each occupation is generated 30 times and responses are categorized into male, female or neutral labelling of the profession in question. The distribution of gender is then contrasted by actual data from the U.S. Bureau of Labor Statistics. Despite that this study originates in computer science, it relies on statistical investigations that are feasible to imitate in a compulsory schools' mathematics education contexts with minor adaptations (Stenkilde et al., 2025). Below, we describe how this is possible by presenting a teaching activity that complies with the Danish lower secondary mathematics curriculum.

In our teaching activity, the teacher initially facilitates an activity to acquaint the students with the notion of bias: students were asked to line up, and the teacher would name a profession (e.g. "pilot"). Following this, students were instructed in stepping either to the left or to the right if they intuitively associated this profession as either male or female. After a few rounds, the teacher was supported in communicating that similar associations are found in online texts, on which language models are trained. Using a translation of the original prompt of Sterlie et al. (2024), our teaching activity instructs students to prompt a small GDPR compliant chatbot, SkoleGPT.dk and record the gender of each person from the output. The students then collect data in a spreadsheet and are instructed to choose an appropriate way of presenting their data. This can lead to a class discussion about the bias that SkoleGPT exhibits and the ideals of GAI. This

sequence follows the principle of *exemplary learning* in that it takes outset in a technology students are likely to have met in their everyday lives outside a school context. While bias might occur in students' everyday encounters with GAI, it is likely to go unnoticed, since it only becomes visible through systematic treatment of the results of many repetitions of the same prompt. This teaching sequence investigates bias systematically through statistics, allowing students to make more generalizable claims based on mathematical investigations. This allows students to consider the potential and implications of a well-known powerful technology based on knowledge and gain insight that although a GAI model performs well in terms of mimicking patterns this might risk causing social harm. This adheres to the second principle and opens for discussions of appropriate social and cultural contexts for its usage: what if a (G)AI model replaces a judge in a courtroom? A job interviewer? Thirdly, this approach implements the principle of alienating the familiar by enabling students to view a technology that they otherwise are likely to consider familiar in new ways.

Discussion

As stated in the introduction, we consider our proposed teaching activity as a humble attempt to expand the increasing interest in CT we have witnessed in STEM context in the past decade. Despite representing a single case, we have made it probable that at least the T and M letters in the STEM acronym possess a significant potential in developing students' Bildung in technological contexts. Our proposed activity is also distinct from the tradition of CT by mainly relying on curricular content within the national curriculum for mathematics. More specifically, the curricular guidelines specify that students should be able to perform modelling processes (including through digital simulations), choose relevant descriptors and diagrams in analyses of datasets and investigate relations in the surrounding society using datasets (Børne- og Undervisningsministeriet, 2019), all of which are integral objectives of the presented teaching activity. In contrast, existing frameworks such as that of Weintrop et al. (2016) propose that STEM teachers embrace new practices (e.g. systems thinking practices, computational modelling practices), which teachers rarely are trained to teach. In addition, Denmark, has not yet implemented technology comprehension into mathematics education. A similar situation is found in England, where the subject "computing" is taught as a separate subject (Bocconi et al., 2022). We therefore believe that the approach presented here perhaps could offer an alternative route, where we can prepare students for a digitalized world by harnessing in-service teachers' existing capacities. This alternative at least seems worthwhile to explore further, not least since existing approaches rely on enforcing and implementing drastic curricular changes that involve significant costs to in-service training and pre-service teacher training reforms.

Conclusion

This paper has sought to address how STEM education on algorithmic bias can contribute to students' Bildung, which is a concept that has received little attention in the CT literature. In our efforts to answer this question, we operationalized ideas of Bildung and technological competence into guiding principles for STEM education and presented a teaching sequence to illustrate the implementations of these principles. This contribution thereby represents an example of how STEM subjects can play an active and important role in preparing students for critical ways of inquiring about powerful technology, that largely has been absent in the international debate on CT.

Our paper has mainly emphasized the role of mathematics and not considered other disciplines from the natural sciences. Algorithmic bias however occurs in many contexts, here among in the use of automated image recognition in medicine that sometimes is more effective when applied

on men than on women. The proposed principles in our paper could aid new ways of activating STEM education towards Bildung objectives.

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IPlan And Simulated Practice In Classroom Settings From A Bildung Perspective

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This paper explores how simulated practice in classroom settings, exemplified by the iPlan platform, can support the development of Bildung—a holistic concept of general education emphasizing personal and societal growth. Science education increasingly incorporates socio-environmental and socio-political issues through scenario-based learning, aiming to bridge abstract knowledge and real-world application. However, such artificial environments risk disconnecting students from physical and social interactions crucial to general education.

By analysing iPlan, a web-based tool for constructing and exploring localized land-use simulations, we investigate how immersive, scenario-based education fosters Bildung. Drawing on theoretical frameworks of epistemic games and scenario-based education, the paper examines three dimensions: (1) how students relate to the world through structured simulations, (2) how they engage and interact with others in these environments, and (3) how the interplay between familiarization and alienation promotes critical reflection and self-development. This contribution highlights the potential of simulated scenarios to balance experiential learning with the cultivation of broader educational goals.

Keywords: Bildung, Simulated Practice, Socio-Scientific Issues, Epistemic Games, Environmental Education

Background: Virtual environments as a way to bring socio-scientific issues to the classroom

Science education is increasingly grappling with harvesting the potential of rich learning environments that simulate socio-political issues and real-world problems related to science (Momani, et al. 2023; Shaffer 2007). These environments provide students with opportunities to explore complex societal challenges, such as those involving environmental sustainability, public health, and technological development. By doing so, they help bridge the gap between abstract scientific knowledge and its application in real-world contexts. This shift reflects broader efforts to align science education with the demands of a rapidly changing and interconnected world. However, such environments are artificial and thus can potentially hinder physical and social interactions with peers and local community that is so important to Bildung.

This paper examines how concerns related to the integration of socio-political issues in science education through interactive digital learning environments can be addressed through the lens of Bildung, or Allgemeinbildung. Rooted in a holistic perspective on formation and development, Bildung emphasizes the cultivation of students' identity, their ability to relate to the world, and their capacity to interact meaningfully with others. It also involves navigating the dialectic between familiarization, that is, understanding and mastering one's environment, and alienation, which involves questioning and challenging assumptions (further explored in Misfeldt, in review). Both Bildung and Allgemeinbildung are weakly defined terms with multiple meanings, but one way of defining Bildung is in relation to the two neighbouring concepts "competence" and "education" (Nordenbo, 2011). Whereas Bildung is an individual self-realization process that deals with an individuals' embeddedness in the world, competence foregrounds the individual's abilities and skills in relation specific situations (Nordenbo 2011, p. 46). In contrast to Bildung and competence, "education" is the infrastructure "that is instituted to prepare the individual to

take part in society's value creation" (Nordenbo, 2011, p. 45).

Following Misfeldt (in review), Bildung can be understood through three interconnected characteristics. First, it concerns the student's ability to relate to the world through Klafki's "double opening," in which the student develops character, skills, and sensitivity, while the world is simultaneously opened to the student through structured and formal educational processes (Klafki, 1991). Second, Bildung involves the student's development across the three domains of qualification, socialization, and subjectification: acquiring knowledge and skills, becoming part of social communities, and developing as a subject with one's own voice, sense of responsibility, and authority (Biesta, 2011). Finally, Bildung entails a dynamic relationship between the familiar and the foreign, where new experiences are internalized while established practices are rendered unfamiliar, enabling a critical stance toward one's own perspectives, assumptions, and norms (Johansen, 2023).

To explore these dynamics, we focus on *iPlan*, an educational technology designed to simulate socio-environmental systems where humans interact with environmental and social processes. Through virtual real-world scenarios, students are encouraged to consider multiple perspectives, engage with ethical dilemmas, and develop a deeper understanding of their roles as citizens in complex, interconnected systems.

The question guiding us in this paper is: How does engagement with a virtual real-world scenario allow students to develop their identity and general education from the perspective of 1) relating to the world, 2) interacting with others, and 3) navigating the interplay between familiarization and alienation?

In this paper, we first describe our theoretical frame that connects literature on virtual internships and epistemic games (Shaffer, 2006) to scenario-based education, then we describe the *iPlan* learning environment before we discuss the question of Bildung.

Virtual Internships, Place-Based Learning, And Scenario-Based Education

Shaffer's (2007, 2012) framework of epistemic frames and epistemic games provides a foundation for understanding scenario-based education (Hanghøj et al., 2017). Epistemic games are computer-supported simulations of professional practices that aim to teach students specific competencies by immersing them in real-world-like contexts. An epistemic frame combines a way of understanding and interpreting a situation with domain-specific knowledge, practices, skills, and ways of understanding that make the scenario meaningful. Shaffer positions epistemic frames as learning goals—perspectives students are encouraged to adopt to engage with these simulated environments effectively.

Building on this, the concepts of frame, scenario, and domain provide analytical tools for understanding how educational contexts are constructed and interpreted (Misfeldt, 2015). A scenario refers to a structured environment or task in which students work, while a frame represents the socio-cognitive structures that enable individuals to interpret and act within that environment (Goffman, 1974). Frames shape how scenarios are understood—for instance, as teaching exercises, competitions, or simulations.

The domain concept highlights the clusters of societal practices and knowledge that inform these interpretations. In educational settings, scenarios often adapt external knowledge practices, blending domains such as schooling, gaming, or professional simulations. Unlike Shaffer's focus on frames as explicit learning goals, this framework uses frames as analytical tools to explore how students make meaning in scenarios and connect them to practices beyond the classroom.

iPlan As An Educational Intervention

To make complex problems personally relevant to learners, one effective approach is to localize them (Siebert-Evenstone & Shaffer, 2019). This situates authentic, real-world problems in learners' own geographic context, leveraging both their experiences of a place and their relationship to a community. However, it is not sufficient for learning simply to transplant complex processes into some specific context, even a familiar one. To cultivate both an understanding of socio-environmental systems and the belief that something can be done about socio-environmental problems, learners need to be able to take consequential actions and see the results to believe that those actions are meaningful (Barab et al., 2009). This can be achieved through reduced-form models, which make complex systems more accessible to learners without compromising the general accuracy of the underlying relationships and outputs. Such models provide the scaffolding needed for authentic interaction with a complex problem, and by embedding them in a local context, learning in the simulation can transfer into the real-world context itself, thus facilitating Bildung.

iPlan (Ruis et al., 2024) is a web-based software platform for constructing localized, reduced-form models of land-use impacts and interactions. *iPlan* models enable learners to (a) construct land-use scenarios (Xiang & Clarke, 2003) that relate specific zoning policies to projected effects on socio-economic and environmental indicators and (b) explore how simulated stakeholders with various and sometimes conflicting priorities react to proposed scenarios. *iPlan* thus enables students, civic representatives, and others without specialized knowledge of land-use planning practices to explore and evaluate possible solutions to complex, multi-objective land-use problems in their local contexts. Critically, it facilitates understanding such problems as intrinsically multidimensional with no single best solution, as the desirability of a given solution is based not solely on rational maximization of objectives but also on social acceptability.

Figure 2. Left: In *iPlan*, the map interface is used to change the land-use class of one or more parcels, and the system computes the projected effect of the change on the selected indicators. Right: Learners conduct experiments (stated preference surveys; Tagliafierro et al., 2016) and use a graphing tool to determine how much change the simulated stakeholders actually want.



Seen through the lens of scenario-based education, *iPlan* allows the development of local models of land use and discusses concerns about them from a number of different perspectives. On one side, the concerns relate to environmental science, nature preservation, and urban planning, while on the other, it involves knowledge about life in the local community as well as the democratic processes allowing different stakeholders to be heard in the process. Working with *iPlan* involves balancing concerns and negotiating trade-offs across these domains. *iPlan* is thus, in one sense, a platform for constructing and solving optimization problems—how to satisfy as many stakeholders as possible in contentious land-use planning processes—but they are optimization problems in which the objectives and constraints must be determined by the learner through

interaction with the simulated stakeholders and deciding which socio-scientific issues to prioritize.

iPlan has been used by thousands of secondary students in both science classes (biology, environmental science, engineering) as well as classes on civics and human geography. Feedback from educators ($N = 23$) is being collected using a semi-structured interview protocol and survey. Of those surveyed, 94% felt that *iPlan* helped them meet their pedagogical goals, and teachers reported that for more than 75% of students, *iPlan* (a) was fun and appropriately challenging, (b) fostered critical thinking about and improved understanding of complex socio-environmental issues, and (c) facilitated exploration of different perspectives on those issues. That is, *iPlan* enabled teachers to construct scenarios that fostered Bildung by enabling meaningful engagement with the socio-scientific processes by which complex decisions about land use are made.

Qualitative analysis also indicates broad agreement from educators that *iPlan* (a) produces realistic, accessible land-use models that are easy to use; (b) supports learning about the relationship between land-use and indicators, multi-objective problems with diverse solutions, the challenge of representing diverse perspectives, and the ways in which scientific and civic practices are interrelated; (c) works well with a range of learners, and in particular with learners who are not engaged by more traditional learning modalities; and (d) facilitates engagement with real-world planning processes. As one teacher from Boston summarized it:

> The iPlan tool is a very realistic modelling tool. It was easy to use for both me and my students and allowed each student to engage with the model at their own level. I loved the fact that we could model our community—I have been struggling to find ways to teach about ecological restoration, and its implications at the local level, that shows kids real world applications, and this tool really helped me do that. My students really buy into learning more when the topic at hand relates to where they live, play, and go to school.

While all educators interviewed to date offered suggestions for improvement or requested additional features, they agreed that the platform addresses their educational needs by providing learners with realistic, localized land-use models in an authentic simulation of scientific and civic land-use planning practices.

Discussion: Educational Scenarios For Allgemeinbildung

According to Misfeldt (in review), Bildung is characterized by three interconnected aspects. First, it involves a "double opening," where the student engages with the world by developing skills, character, and sensitivity, while education provides structured, formalized ways of presenting the world to make it accessible and meaningful (Klafki, 1991). Second, it encompasses development across three arenas: acquiring knowledge and skills (qualification), integrating into communities and social structures (socialization), and fostering autonomy, responsibility, and a unique sense of self (subjectification) (Biesta, 2011). Finally, Bildung addresses the dynamic relationship between familiarization and alienation. Students internalize foreign experiences, making them familiar, while also using new knowledge to critically examine and challenge established norms and practices, enabling a reflective stance on their origins (Johansen, 2023).

Bridging concerns across different domains—whether scientific, social, or personal—is a powerful way to cultivate diverse ways of relating to the world. Structured learning environments like *iPlan* provide a platform for this kind of engagement, allowing students to navigate scientific reasoning while situating their learning within the context of their local community and authentic decision-making praxis. This embeddedness enhances both individual and personal relevance, making abstract knowledge more tangible and applicable.

Empirical findings highlight the importance of physical context in shaping learning experiences. The fact that learning takes place in a familiar, real-world setting rather than an abstract or imagined place influences how students connect knowledge to their own lives. Moreover, *iPlan* serves as a training ground for integrating scientific understanding with personal identity and social responsibility, encouraging students to take a stance on local issues where multiple perspectives and conflicting concerns intersect.

A critical factor in this process is the *artificial* nature of the learning environment. While it provides structure and scaffolding, it also raises important questions: How does the simulation of local engagement impact students' formation and Bildung? To what extent can such artificial yet contextually grounded settings foster authentic, reflective engagement with real-world issues? These questions remain open for further empirical investigation.

While the educational value of these types of learning environments is well-documented, their broader potential in supporting Allgemeinbildung remains less explored. The capacity of structured yet flexible educational spaces to cultivate critical reflection, ethical reasoning, and meaningful connections between knowledge and lived experience is evident. However, further research is needed to fully understand how such models can contribute to Bildung in a way that transcends disciplinary knowledge and fosters holistic personal and civic development.

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Wondering To Relate To The World In The Science Laboratory

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In contemporary education, science is often described as a domain of certainty, grounded in logic and facts, detached from human influence and judgment. This description marginalizes the role of uncertainty in science education to be not-(yet)-scientific: It relegates concerns about how to describe complex problems to be preliminary stages of scientific inquiry or simply a lack of knowledge.

The view of science education as detached from human judgement is one of the reasons highlighted for why science education should play a smaller role in students' subjectification processes compared to other educational subjects. To critically reflect on this, we re-visited an analysis of concerns around science in 14 classes of 8th-graders visiting a science educational laboratory. Drawing on Thévenot's sociology of regimes of engagements and Ingold's distinction between orientation to the world through wisdom and knowledge, we compare how different engagements with the subject enables different orientations to the world. Engaging narrowly focused on solving a task tends to emphasize moving from the world to the subject matter, thereby not allowing the student to relate to the world through the subject matter. It reflects an idealization of exploration of the self in the subjectification that requires an according engagement from the student.

Keywords: Doubt, Subjectification

Uncertainty And Science Education

In school, science is most often considered a stable topic relying on logic and facts, detached from human influence and judgment (Christensen & Fensham, 2012). Simplistically put, this means that uncertainty is essentially "outside the core" of science because it bridges to political domains (such as debates about the placement of windmills and nuclear power plants, or the mitigation of food scarcity through gene modification) or is seen as an early and temporary stage (a "hook") that precedes explanation and structured investigation (Bybee, 1997).

This stable picture of science education contrasts with Gert Biesta's view of education as an inherently fragile phenomenon, characterized by risk and uncertainty. In his book, "The Beautiful Risk of Education" (2015), he argues that this uncertainty arises because educators can never fully predict how individuals will shape their identities and worldviews in response to educational experiences. Education, he argues, should be a phenomenon that involves open-ended processes where students actively engage with ideas and form personal understandings.

This view is not in opposition to a focus on development of skills and competencies. Rather, Biesta replaces a one-dimensional output-oriented learning and accountability focus with a fragile interplay between three arenas of education; qualification, socialization and subjectification (Biesta, 2010). An educational process is a process of "becoming" in all three arenas. The fragile nature of education means that students' development in any of these arenas cannot be completely scripted.

In line with Biesta, this proposal addresses how students reflect and relate to the world through science. Here, we are inspired by the interplay between the adolescents' experiences outside of the science laboratory, and how they get to play a role in their interaction with the content in the activities. Here, we are inspired by Ingold's distinction between *knowledge* to predict the world

through models and *wisdom* be able to relate to the world through knowing what to put attention to (Ingold, 2023).

By understanding engagement as important for what kinds of doubts one asks of the environment (Hansen, 2023; Thévenot, 1990), we seek to understand how different engagements enable either a predictive or a relational engagement with the world. Based on this understanding, we ask the research question: What kinds of relationships with the world do different orientations of doubt make possible for students?

We answer these questions based on findings from one of the author's PhD projects on doubt and group work in the science laboratory. Drawing on fieldnotes from observing 14 grade-8 classes as they visited a science activity center, we investigate how the students' science content-based doubts with different orientations (task/not-task) lend themselves to different reflections on and with the world outside the laboratory.

We find that the orientations of doubt allow students to relate to the world in different ways. We argue that when students wonder to explore new things with the science content, they make room for differentiation, most closely in line with the emphasis in subjectification. However, we argue that in subjectification, there is an orientation towards the self that is not granted in the students' relations between the laboratory and the world.

Theory: Engagements, Doubts, And Relating To The World

As outlined in the introduction there is an ideal of educating oneself to use the competencies of the subject matter to relate to the world. Here, we draw on Tim Ingold, who is concerned with what kind of attention we turn towards the world (2023). He describes one way of having attention to the world through knowledge, which he describes as trying to recognize systems or causalities, and thereby being able to predict the world. He distinguishes this from relating through wisdom, with which one can see differences or newness in the world, based on an existing framework (Ingold, 2023). To understand different ways of thinking about the relationship to the world, we think with the sociology of regimes of engagements (SRE) (Hansen, 2023; Thévenot, 2006). SRE asks how one can engage with the world depending on the disposition of the environment (ibid.). This disposition originates from markers of regimes of engagement, which the actor remarks on, and from this composes a fitting engagement. This process of remarking can lead to doubt through a dual process of remarking on what the potential outcome of an engagement is and what costs might be associated with following it.

Table 1. Inspired by (Hansen, 2023)

	Familiarity	Plan	Justification	Exploration
Evaluative good	Ease, comfort, convenience	Getting planned things done	Qualifies as a common good	Excitement of something new
Positions of doubt/trust	Routinized / groping	Indecisive/decisive	Contested/justified	Detached/faith in discovering
Examples of doubt	Is this how it is usually done? Is this pleasant? (bodily unease)	Is this productive? Is this beneficial for a goal?	Is this just? Is this morally right?	Is this new? Is this different?

The sociology of regimes of engagement introduces four different regimes for engaging; the regime of familiarity, the regime of the plan, the regime of justification, and the regime of discovery (Hansen, 2023). Each regime allows a different relationship with the world and thereby a different type of doubt as exemplified in Table 1.

Following the sociology of engagement, there is a plurality of ways to engage with the world,

each bringing different types of doubt. It is important to note that the sociology of engagement's definition of doubt is broad, including pre-reflexive- or non-verbal doubt (i.e., the unease one might experience when trying something new). In this analysis, we are focused on students' verbalized doubts, which assumes a level of reflexivity that makes us blind to more pre-reflexive doubtful moments.

Method

The empirical study on which this proposal is based is informed by the first author's field observations from following 14 different 8th-grade classes as they visited the science center for a day (Nøhr, in review). The students worked in groups of 2-4 to solve tasks such as computer programming an automatic water pump, examining microorganisms under a microscope and creating an experiment to increase bacteria in a sample.

Due to the limited amount of time and the number of students, the researcher focused closely on one or two groups during their visit. Following traditions from informed grounded theory, the selection of groups was done as the research progressed, allowing findings from the initial parts of the research to influence the selection of groups and the focus in subsequent visits. The biggest change throughout the fieldwork was a shift from an initial interest in students' experiences of failure to a focus on their experiences of uncertainty.

Results

The initial analysis of the empirical material showed an interesting distinction in the students' doubt during the lessons, namely whether the doubt is oriented towards the task and whether it is based on the teaching content (Nøhr, in review). Based on the distinction between task-based and non-task-based doubts, we compare the engagements of the students.

Table 2. Doubts in the laboratory.

	(orientations) Task-based	*(orientation) Not task-based*
Content-based	Task doubt working with the curricular content	Content-wondering
Examples of non-content-based doubts (for reference, not discussed)	*Instrumental task-doubt*	*Not subject-related*

The task-doubt: is doubt oriented towards getting on with the task based on discussions of the content matter. For example, a group of students is asked to increase the amount of bacteria in a sample by adding a variable, where they can choose between acid, sugar, salt, increasing- or decreasing the temperature, or changing the amount of oxygen. One student suggests adding salt and sugar, leading to a discussion about whether there is a difference between salt and sugar. This distinction is important for the students as it determines whether they are adding one or two variables if they add both. In their argumentation, the students bring in examples from the world outside the lab, such as discussing whether one would add salt to tea. The orientation of the doubt is on solving the task through discussing the content, and the students do not return to the implications of salty tea.

Task-doubts are by definition focused on solving a task, so it is not surprising that the students' engagements follow the regime of the plan. However, doubts about whether salt and sugar are the same could be viewed as a compromise between the regime of the plan and the regime of exploration. While the playfulness of discussing the tea is evident, which is most commonly associated with the regime of exploration, it still contributes to the overall aim of solving the task. In terms of the connection between science and the world, the example of tea brings the students'

everyday life into the science classroom. Ultimately, it should contribute to the students' understanding of the experiment, making it important in the situation that they conclude that salt and sugar are not the same.

Wondering: is doubt based on the subject matter but not related to the task at hand. For example, three students discuss what it means that humans have high conductivity, leading them to wonder whether one could replace cords with dead people. A less morbid example is a student who thinks that their microorganism is a vertebrate, and who then starts discussing with their teachers what makes a vertebrate a vertebrate.

As wondering is not oriented towards solving the task, it aligns with regimes other than the plan. An important type of doubt involves questions about whether things are different or where they originate from, following the regime of exploration. In terms of the connection between science education and the world, the example of microorganisms brings the science concepts out of the laboratory and allows the students to see the world through these concepts.

The Role Of Uncertainty, Doubt And Wondering In STEM Education

Doubts in science teaching are not limited to discussions, value judgements (based on stable results), and early-stage investigations. Instead, students face doubt throughout the process of solving their tasks. Here, task-doubt provides a possibility to think about the science content through their everyday lives – letting the adolescents' everyday life be an arena that they can think the concepts through with, a knowledge-oriented attention. Simultaneously, during their time in the laboratory, wondering leads students to reflect on the implications of the content matter outside the laboratory, in the world as they know it. This is more aligned with a wisdom-oriented-attention, trying to see differences based on the subject content.

This delicate relationship between the science content and the students' everyday life illustrates Biesta's point about education being an interplay between qualifications, socialization, and subjectification processes. Students reflect on the world as they know it through their understanding of the concepts, and on the concepts through their understanding of the world.

One key difference between the two orientations of doubt (task-doubt vs wondering) is the kinds of engagement with the world the doubts lend themselves to. As the impetus in the task-doubt is to get on with the task, this is also the type of engagement it allows. Engagements to fulfill the plan and solve the task are thereby bound by the logic of the task (as also argued in Nøhr, in review).

Relating this back to subjectification processes, what is the role of science as a subject then? In the above examples, the relationship between science concepts and students revolve more about attention on the world or attention on the task, but less so on the students themselves. Whether science has a role to play for the subjectification processes then has to be readdressed as a question of what type of subject – and in particular, how self-reflexive a subject – is implied in the subjectification-emphasis. Doubt is present in classrooms and laboratories, but whether it orients itself to a knowledge- or a wisdom-oriented attention is made possible through the dispositions granted in the teaching.

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"That Coordinate Is A Clue!": Exploring Teachers' Sense-making In Interdisciplinary Tasks

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This contribution reports on a teacher professional development activity within a research project investigating how to foster teachers' awareness in interdisciplinary contexts. The teachers involved have a background in either mathematics or physics and teach both subjects in Italian high schools. This requires them to deal with interdisciplinarity. We present the design of a task that explicitly aims to create a boundary space between several disciplines and to promote multiple ways of reasoning and multiple possible goals. Teachers were asked to work on the interdisciplinary task first in small groups and then encouraged to share their reflections in a collective discussion. The findings report both a summary of the themes that emerged from the collective discussion and the insights from one group work. The macro-themes relate to exploring the causes of the oil slick, interpreting changes in the coordinates of a pin, building models of the expansion of the oil slick, and searching for the meaning of the color variations. Their disciplinary relevance is also highlighted by an a-priori analysis carried out by three experts. We also report interactions that instantiate teachers' sense-making processes both backward, to define the problem by interpreting the perceived details as available data, and forward, to search for new data to support relevant objectives they have elaborated autonomously. Finally, we discuss the alignment of the implementation outcomes with our design intentions and suggest further steps for helping teachers build on their insights from the discussion to foster interdisciplinary awareness.

Keywords: Professional Development, Scientific Argumentation, STEM Education

Introduction

This contribution reports on a secondary school teacher professional development activity held within a research project aimed at investigating how to foster teachers' awareness of disciplinary assumptions and postures adopted in sense-making processes.

Such awareness is essential for teachers who, despite having a background in either mathematics or physics, are required to teach both subjects, thereby necessitating engagement with interdisciplinarity.

Indeed, interdisciplinarity is a profound relationship between disciplines which share not only knowledge, but also aims and values, methodologies, and practices (Erduran & Dagher, 2014). This relationship is instantiated through boundary objects, boundary crossing and boundary people (Akkerman & Bakker, 2011) that allows to create a metaphorical space of encounters, reasonings and negotiations of meanings between disciplines and their actors.

A valuable framework for understanding and structuring the reasonings and sense-making processes activated by a task designed to create a boundary space is provided by Habermas' rationality (Habermas, 2003). It comprises three components: epistemic, involving the validation of claims based on shared premises and legitimate argumentation modes; teleological, entailing the deliberate selection and use of tools and strategies to achieve the activity's objective; and communicative, including adherence to rules ensuring both the ability to communicate the steps

of argumentation and the conformity of the outcome with the standard or target reference.

Here we present excerpts from the teachers' interaction, audio-recorded during the activity, while engaging in an interdisciplinary task specifically designed by researchers (see next section). Teachers solved the task in small groups (3-4 teachers and one researcher per group) and then discussed it collectively guided by the researchers. Through Habermas' lens, we analyse the teachers' reasoning to shed light on whether the task effectively creates a boundary space that elicits the development of disciplinary and interdisciplinary awareness.

Task Design

The interdisciplinary task was specifically designed by the researchers as open-ended and "undisciplined" (Williams & Roth, 2019) as possible.

Figure 1. The original task (left) and the redesigned task (right).



The redesigned task (Figure 1, right) was inspired by an item from the Italian 2014 Standardised Assessment in Mathematics (Figure 1, left), which targeted 8th-grade students. The item featured a schematised representation of an oil slick and a multiple-choice question designed to test students' computational ability to approximate areas, focusing the assessment on specific procedural mathematical skills within a narrowly defined topic. This version was limited in scope: the schematised image and narrowly defined computational question constrained both disciplinary focus and cognitive engagement, reducing the task to a static and technical exercise. Redesigning the task, researchers significantly expanded its original structure to foster interdisciplinary reasoning and dynamic exploration. The schematised drawing was replaced with a series of timestamped satellite pictures showing the evolution of the oil slick over time. This transformation introduced authentic, unfiltered data, removing any preliminary selection of what might be considered relevant. As a result, the task required the identification and interpretation of key information, reflecting the complexity of real-world scientific inquiry.

The question in the task also evolved from a precise, computational prompt "The extent of the oil slick is" to an open-ended inquiry "What can be said about the oil slick?". This redesign positioned the task to engage in undisciplined reasoning, bridging mathematics with physics and environmental science. By presenting a real-world, evolving context, the task moved beyond static reasoning, encouraging reflection on the interplay between disciplines.

Specifically, the deliberately vague question and the authentic data, which lacked explicit clues about the problem-framing or the disciplinary approach to adopt, were deliberately intended to elicit teachers' sense-making and nurture their reflective awareness regarding their postures and strategies when addressing interdisciplinary tasks.

An *a-priori* analysis of the interdisciplinary task was carried out by three experts: a university physics lecturer and two teachers with expertise in physics education research (PhD). The primary concern is the clarity of the guiding question, whose phrasing is considered too vague by the physics lecturer. It is considered thought-provoking but demanding by the two teachers with expertise in physics education research since the task presents a real-world complex issue with multiple influencing factors, including ocean currents, wind, and oil density. Both stressed that it is essential to define the problem before solving it (*problem-framing* vs. *problem-solving*) and that qualitative and quantitative questions should be refined to make it possible to investigate the problem. Concerning possible goals of a problem-solving activity, they mentioned characterizing the oil slick size and tracking the slick movement. The area-perimeter ratio could offer insights into the potential fractal nature of the slick. Critical issues highlighted by all the experts concern the satellite images:

1. Distinguishing the slick from the background becomes increasingly difficult as it spreads;
2. Higher-resolution images would enhance the accuracy of this analysis;
3. Some key contextual details are hard to interpret, such as the meaning of the arrow and the coordinates.

Findings

The reflections reported during the collective discussion can be categorized into four themes, aligned with the a-priori analysis:

1. Causes that led to the formation of the oil slick;
2. Changes in the coordinates of the map pin shown over days;
3. Models related to the expansion of the oil slick;
4. Meaning of the colour variations in the oil slick.

The coherence between these themes and the *a-priori* analysis underlines their disciplinary relevance, and their variety allows for the evaluation of the task both in realizing researchers' intentions and in its effectiveness as part of the activity.

Specifically, regarding theme 1, the teachers hypothesized possible atmospheric causes for the altered climatic conditions leading to the creation and expansion of the oil slick, such as typhoons or tides. This theme sparked further reflections during the collective discussion about the fact that the images only allow to formulate hypotheses about what is visible. Observable elements can be described but it is impossible to determine what happened before or after. Regarding theme 2, one group reported that they first hypothesized what the pin might represent, such as the oil platform's location, and examined the coordinate changes across images. Regarding theme 3, one group attempted to approximate the slick's area by inscribing it within rectangles and applied this procedure to all the images to construct a graph of the slick's area trend over the days shown. They also questioned whether such a model could predict future expansion of the slick. Finally, regarding theme 4, one group considered whether grey, yellow, and blue shades might indicate the slick's consistency (e.g., dark grey for dense and compact patches, yellow for dispersed areas). The colour issue also prompted other groups to share their reflections. They noted that they used colours to distinguish the slick from the coastline.

The variety of themes emerges not only during the collective discussion but also in the group work. For instance, the group that ultimately focused on coordinates had previously touched on multiple aspects, revealing observations such as “area size” and “density” that could have been explored further.

This diversity seems linked to the undisciplined nature of the task, allowing teachers to explore and make sense at varying depths of those details that draw their attention.

These details can serve different purposes for the teachers, either within a single image, such as estimating the slick’s area on April 25th (“You can estimate the area, right? I mean, here *[the scale]* this is 20km”), or in comparing images, as in the following case where a teacher tries to distinguish the slick from the mainland:

> ***TeacherA***: If this little pin had not been there, I would have (...) thought [the oil slick] was that one [the mainland]. But since it [the mainland] stays fixed over time (...) I would say that it is land (...) if what changes is the shape [of the oil slick] over time.

While identifying the pin coordinates, the group focused on calculating their change and concluded that it is of 1deg up, equivalent to 100km:

> ***TeacherA***: Maybe I got it all wrong, but if this [the scale] is 20km (...), 100km would be 5cm. Now, it clearly has not moved 5cm since (...) the scale is the same!
>
> ***Researcher***: Actually, you are trying to make sense of the numerical data provided.
>
> ***TeacherB***: Yes, it is the only data available (...) When it comes up, the difference itself is... a clue (...)
>
> ***TeacherA***: That coordinate is a clue!

The previous episode shows a case where teachers not only show epistemic control over familiar data (such as calculating and interpreting coordinate differences) but also interpret details as “clue(s),” intentionally embedded by the designers to guide them toward an as-yet-undefined-but-expected objective (for them).

This relationship between data and objectives differs from a search for data to pursue explicit goals, aligned with the teleological dimension of rationality, as in the following interactions:

> ***TeacherA***: What do you think are the causes of this spread? (...)
>
> ***TeacherC***: Essentially, ocean currents (...).
>
> ***TeacherA***: I also think the weather plays a role, in addition to the currents (...)
>
> ***TeacherC***: Can we Google the weather for May 2010 in the Gulf of Mexico?

These cases underscore how the group worked backward to define the problem by interpreting the perceived details as available data, and how they would have worked forward to search for new data. These processes reflect dynamics between the observation/search of data and the identification of “achievable” objectives.

Conclusions

The teachers’ reactions stimulated by the task seem to be aligned with the redesign choices. The multi-faceted collective discussion and the group work show the ability of the task to elicit reasoning, encouraging reflective engagement with possible data interpretation, sense-making strategies, and autonomous objectives-structuring instead of adhering to predefined ones. For instance, the suggestion to search the web for the weather conditions is an example of how the sense-making process was not limited to what was explicitly provided. Teachers were also

engaged at the epistemological level in the meaning and interpretation of the data. The episode about the coordinates is an example of how they moved beyond their simple application, focusing on their nature and questioning their significance in such a context. Finally, the mentioned alignment emerges in terms of problem-framing. For instance, the decision to provide multiple sequential images may have promoted episodes of dynamic exploration, in which teachers considered not only static features but also the evolution of the phenomenon over time.

The findings highlight the potentialities of the re-designed task in supporting interdisciplinary-disciplinary awareness when working in boundary spaces, where teachers could engage in diverse processes connecting disciplinary perspectives. At a broader level, this aligns with our overall goal: since Habermas' rationality lens possibly offers a valuable framework for investigating interdisciplinary processes, to what extent can it be integrated into a professional development program? The present study offers an initial answer by analysing how teachers engaged in a task designed to prompt such kinds of reasoning. In a following activity, teachers were guided to reflect on how the lens of rationality offers dimensions for analysing their own reflections on the task and classroom activities more generally. Future research efforts will explore how to bridge teachers' work directly with Habermas' framework and their insights emerging from the task-related discussion to foster interdisciplinary awareness.

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Section: Interdisciplinary Teaching And Learning Design For Cross-Cutting Concepts

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Unpacking Measurement Devices: Transduction And Multimodality For Blending Mathematics And Physics In Teacher Education

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This exploratory study investigates how the analysis of measurement processes and transduction mechanisms can support the integration of mathematics and physics in teacher education. Framed within a socio-semiotic perspective on multimodality, we conceptualise teaching and learning as the result of cognitively and affectively motivated choices among available meaning-making resources. Building on work by Duval, Bezemer and Kress, Airey and colleagues, and others, we distinguish between semiotic and non-semiotic representations and between intra-modal transformations (treatments) and inter-modal transformations (transductions). We then use these constructs to examine how mathematical and physical reasoning can be blended rather than separated. The empirical context is a teacher training course (February–June 2023) within the Multidisciplinary Laboratory Teaching project at INDIRE, involving a working group of researchers and eight secondary school mathematics and physics teachers. The group collaboratively designed and analysed experimental activities centred on motion and measurement, with particular attention to the functioning of motion detectors as paradigmatic "black-box" instruments. By progressively unpacking the internal mechanisms of such devices—analogue and digital, continuous and discrete—the teachers explored transductive chains linking bodily action, sensor signals, graphs, and formal mathematical expressions. Video-recorded and transcribed meetings were cross-analysed to identify key epistemological and didactical themes. Two transversal foci emerged: (1) the role of transduction and measurement in mediating between continuous physical magnitudes and discrete numerical structures; and (2) the interplay between analogue and digital representations in contemporary measuring instruments. The findings suggest that treating transduction and measurement as central scientific practices offers a promising educational alliance for overcoming the perceived gap between formal mathematical entities and the modelling of physical phenomena, while also fostering teachers' critical engagement with technology and multimodal classroom design.

Keywords: Transduction and transformations, measurement, physics, mathematics, socio-semiotic, treatment and conversion

Theoretical Background

Teaching mathematics and physics presents challenges due to the perceived disconnect between the two disciplines (Osborne, 2023). Blending these two disciplines involves more than merely introducing mathematical concepts through physical examples. Instead, the focus should be on recognising the unity of cognitive processes that underpin the understanding of interconnected concepts and structures in both disciplines. In recent studies, Kapodistrias and Airey (2024, 2025) examine mathematical functions in physics and how they, in turn, shape physics education. It begins by emphasising that mathematics has historically been regarded as central to physics, with influential figures such as Feynman, Einstein, and Hertz arguing that meaningful physical laws and even nature itself are deeply mathematical. Mathematics is thus often described as the language of physics. This central role of mathematics has important consequences for education. A recurring issue in the literature is the tension between mathematics as a technical, computational tool and mathematics as a means for conceptual, physical reasoning. Many studies show that students can successfully perform calculations, such as solving quantum mechanics

problems or computing the curl of an electric field, without truly understanding the underlying physical concepts (Johansson et al., 2018; Airey & Linder, 2017). Educators, in turn, often struggle to design problems that promote conceptual meaning-making instead of pure computation. These difficulties motivated the development of Conceptual Physics (Hewitt & Baird,2014), an instructional approach that treats mathematics as a potential barrier to understanding. In this view, instruction should begin with building a strong conceptual model of the physical situation, and only once this understanding is established should mathematical formalism be introduced. However, other researchers argue that sharply separating conceptual understanding from mathematics is not always appropriate (Uhden et al., 2012; Redish & Kuo, 2015). Rather than treating mathematics and conceptual reasoning as distinct phases, they investigate how mathematics itself can serve as a vehicle for conceptual thinking. Some of this work describes students' mathematical problem solving in terms of scientific thinking strategies, or epistemic games, that they engage with when using mathematics in physics. Others focus on what students mean when they say they "understand" a physics equation, examining this from an epistemological standpoint. Building on these ideas, several models have been proposed that integrate mathematical and physical reasoning instead of keeping them apart. Uhden and colleagues (2011) claim that physical (conceptual) and mathematical (quantitative) models should not be separated in physics education and instead propose a model in which the two co-exist as part of a unified physical-mathematical reasoning process. Redish (2006) offers a related framework in which using mathematics in science involves mapping physical quantities to mathematical expressions, processing those expressions, interpreting the mathematical results back into the physical world, and finally evaluating whether the results are adequate.

The present work constitutes an introductory, exploratory study within a broader research project. The goal is to study the impact of unpacking and repacking a measurement mechanism (i.e. a motion detector) to foster its pedagogical and disciplinary affordances (Kapodistrias & Airey, 2025) in a teacher-training context. The study is framed within socio-semiotic theory (Bezemer & Kress, 2008) and the multimodal activities that arise from transduction and transformation (or conversion and treatment) in mathematics and physics classrooms. Key concepts such as socio-semiotic theory, multimodality, transduction and affordance will be briefly outlined.

Socio-Semiotic In Math And Science Education

Following Cobley (2001), semiotics can be understood as follows: "In a general sense, a culture can be seen as a typical configuration of choices derived from various semiotic resources. Semiotics itself is the study of semiosis, which is the process of producing signs". In other words, it is possible to study a specific community—such as science classrooms—through the meanings of the signs it produces. Michael Halliday, through his theory of Systemic Functional Linguistics, was the first to introduce a distinctly social orientation into semiotic theory. Halliday (1978) argues that the meanings of signs, or semiotic choices, are shaped by social context and negotiated within social and cultural environments (Halliday, 1978). Since the 1990s, scholars have further extended socio-semiotic studies to a variety of subfields, including popular culture, multimedia, and disciplinary domains such as science and mathematics. In this perspective, the volume Multimodal Teaching and Learning: The Rhetorics of Science Classrooms (Ogborn et al., 2001) has made a substantial contribution to science education. The authors conceptualize multimodality in teaching and learning science as the coordinated use of multiple semiotic modes—language, gesture, visual representations, and bodily movement—through which scientific activity in the classroom is conducted and can be observed. Social-semiotic theory has significantly reshaped how learning and teaching processes in science and mathematics education are conceptualised. In line with Kress et al. (2001), we adopt the following view: teaching and

learning in the mathematics and science classroom are the "evidence" of the cognitively and affectively motivated choices of teachers and students from among the meaning-making resources available in a particular situation (the classroom) at a given moment. In mathematics education, Luis Radford has devoted numerous studies to the meanings of signs in mathematical activity (see Radford, 2002; Radford et al., 2003). In (Radford, 2002), he introduces the notion of the semiotic node to describe the coordination of different semiotic modes (e.g., action, gesture, word, drawing) in students' activity. To identify these nodes empirically, Radford and his colleagues (2003) designed an experimental study in which students represented the spatiotemporal graph of a body's motion. Their data showed that this context was particularly suitable for observing the emergence of semiotic nodes (Radford, 2002).

Transduction And Conversion

Semiotically, two types of change have been noted: transformation and transduction (Bezemer and Kress, 2008). Transformation involves changes to the object of learning within the same semiotic system (mode), and transduction involves moving semiotic material from one mode (or semiotic system) to another. This transfer can significantly alter the potential meaning of the material (Volkwyn et al., 2019).

In physics education, Airey and colleagues discussed transduction in physics education extensively while Tuminaro and Redish (2007), for example, describe how students often resort to "plug and chug" strategies, where "plug" denotes substituting numerical values into equations and "chug" denotes carrying out algorithmic transformations to obtain a result. Instead, Arcà and Guidoni (1987) define it differently: transduction is the conversion of an input signal into another type of signal via a specific interface. In this context, transduction reveals the functional relationship between two interacting variables and thus represents a specific instance of the broader socio-semiotic framework.

In mathematics education research, Duval (2006) identified the same definitions under different names, distinguishing two aspects of mathematical activity: conversion and treatment. Conversions are transformations of representation that consist of changing a register without changing the objects being denoted. Treatments, by contrast, are transformations of representations that happen within the same register: Duval (2006) argues that "passing from one register to another [makes] explicit other properties or aspects of the same mathematical object." When the object of learning is moved across different representational modes—word problems, graphs, equations, and so on—different facets of mathematical knowledge are made explicit; in meaning-making terms, different meaning potentials are unlocked (Airey & Linder, 2017).

Moreover, Duval distinguishes representations between:

1. Semiotic representations: produced through systems of signs (natural language, mathematical symbols, codified diagrams, graphs with conventions, etc.). Here the relation between object and representation is conventional and governed by the rules of a system of representation.

2. Non-semiotic representations: produced by physical devices (mirror, camera, microscope…) or by sensory and brain organizations. Here the relation between object and representation resembles a causal relation: the object (or phenomenon) produces, so to speak, an "effect" on the device or on the senses. In other words, on-semiotic representations produced by physical devices may be regarded as a particular mode of access to the object, in which the "sense" is strongly constrained by physical causality (for example, an image in a mirror, a trace on a screen, a photograph of the phenomenon, an instrumental measurement, etc.).

This work discusses how the same phenomenon, such as motion, can be represented through various senses: some are semiotic, like equations, graphs, natural language, and diagrams, while

others are non-semiotic in Duval's sense, such as experimental traces, instrumental measurement, and sensor readings, which are linked to the object through causal relations. Blending mathematics and physics involves connecting these two types of representations within a multimodal teaching and learning environment. In this sense, the connection between mathematics and physics is evident in the transduction processes.

Therefore, analysing the internal workings of physical mechanisms is an excellent opportunity to clarify the relationship between theoretical entities and measurement processes. Depending on the nature of the transducers (e.g., analogue, digital, mechanical, electrical), learners may observe straightforward correlation patterns or discern a more pronounced cause-and-effect relationship that informs their understanding of the phenomenon's operating principles. Measurement intrinsically implies the concepts of numbers and countability, which emphasise the psychological underpinnings of mathematical concepts. This link suggests a profound connection between understanding and perceiving mathematical abstractions and the ability to measure and quantify physical properties.

Furthermore, the examination of transduction highlights the crucial role of technology from an engineering viewpoint. The accuracy of the conversion between magnitudes (e.g., linear, quadratic, cubic) is closely linked to geometric constraints. Understanding the apparatus's geometry allows one to grasp the benefits and key steps of a particular conversion process. In physics, exploring the internal mechanisms of machines and measurement devices provides a significant opportunity to clarify the relationship between theoretical concepts and measurement practices. During the modelling process, familiarity with both historical and modern machines, as well as transducers, is of considerable cognitive value. The mechanical metaphor is foundational for all cause-and-effect reasoning and is essential in physics. In mathematics, mechanical drawing machines serve as valuable tools for dynamically studying notable curves. Analysing geometric and motion transformations (e.g., linear versus circular) alongside transduction processes enables students to understand fundamental concepts in mathematics and physics while developing advanced technological skills.

Materials And Methods

This contribution outlines the activities and outcomes of a teacher training course that utilised experimentation to explore the limitations and potential of introducing the analysis of measurement instruments and their functioning mechanisms in educational practice.

The course, held between February and June 2023, is part of the Multidisciplinary Laboratory Teaching project at the National Institute for Documentation, Innovation, and Educational Research (INDIRE). The Working Group (WG) comprised two researchers in math and physics education and one researcher from INDIRE, and eight secondary school mathematics and physics teachers. The group met monthly for 2-hour session meetings over 4 months.

Regarding teacher education, research increasingly underscores that teachers' attitudes and beliefs influence how science subjects are taught. Numerous studies have demonstrated a strong correlation between teachers 'attitudes and beliefs regarding teaching methods and subject content and their success or failure in teaching practices (Jones & Carter, 2006; Bryan, 2012; Jones & Legon, 2014; Wallace, 2014). In this area, the proposed training model (Amabile et al., 2022) connects teaching practice with scientific research. This approach enables the transformation of field-based experimental results into valuable suggestions for teacher training and the reassessment of teaching practices. Such an approach can lead to didactic proposals that resonate with classroom practice, promoting a bottom-up rather than a top-down approach.

The proposal seeks to incorporate a carefully crafted analysis, along with a series of practical

field experiments conducted over the years, which are well documented on the research group's website (www.les.unina.it). The aim is to examine the processes of transduction and measurement as exemplary educational practices and transversal cognitive frameworks within both disciplines, and to assess their effectiveness in bridging the apparent gap between the teaching and learning of mathematics and physics.

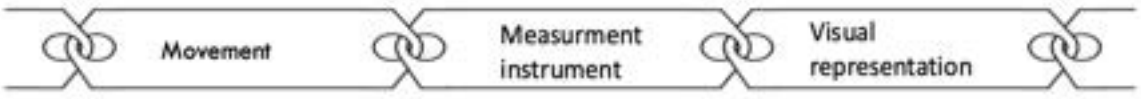
A valuable theoretical tool for designing educational activities that integrate mathematics and physics is the transductive link (Svesson & Eriksson, 2020). This link is any semiotic system that facilitates the transduction process between two different semiotic systems. It can be a single link or part of a short chain, or it can comprise multiple links forming a longer chain. For example, a lengthy transductive chain might be a physics project in class, where the properties of the chain depend on its context and purpose. According to Svensson and Eriksson, this concept can be a useful design and evaluation tool, helping to focus on the consistency of semiotic material flow between different modes.

Experimental Activities

As first activity, a video is presented in which a group of children moves their bodies back and forth, in a wave-like motion. To support temporal coordination, the children are instructed to clap when their bodies reach the forward position. Simultaneously, a motion detector records only the first child's movement, positioned at the head of the row, and displays it on a screen. While observing the screen, the children continue their movements.

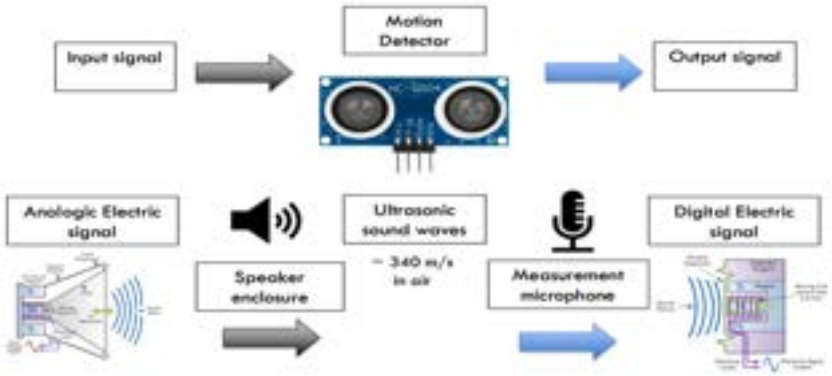
The video illustrates a multimodal activity that represents a specific motion in a collective and real-time manner. The measurement process plays a fundamental role, as it relies on a motion detector that, at present, functions as a black box. It is hypothesised that this activity could be repeated multiple times to support children who experience difficulties coordinating their bodily movements, especially in relation to others' movements. The transductive chain of the activity is showed in figure 1.

Figure 1. Transduction chain associated with the activity shown in the video.



Successively, it appears essential, on the one hand, that teachers acquire the ability to design experimental activities that exploit the potential of technology to activate multiple learning modalities, and, on the other hand, that they become aware of the implications of using black-box instruments, which can empower them and foster critical thinking. One possible approach is to develop an unpacked model of such black-box instruments.

Figure 2. Transduction processes and unpacked motion detector scheme.



Several experiments were designed to measure the velocity of ultrasound waves during an object test. The functional mechanism was discussed, and a representative diagram highlighting the differences between analogue and digital equipment was created as shown in Figure 2. The operation of the motion detector sensor is then examined, focusing on the transduction processes involved. Thanks to advances in microelectronics and programmable sensors, it is now possible to explore the sensor's internal structure, effectively unpacking the black box and revealing its internal mechanisms (see Artiano et al., 2025). This understanding helps teachers familiarize themselves with the technology and recognize its pedagogical and disciplinary affordances in educational settings.

Results

During the meetings, the WG highlighted several key concepts that were both broad and transversal. The topics addressed by the study group included investigating the phenomenological aspects of motion through two main subthemes:

1. The transduction and measurement process between continuous and discrete;

2. The transduction and measurement process between analogue and digital.

The meetings were recorded on video and transcribed. The resulting content was then cross-analysed. The analysis's findings are presented below as a report on the activities undertaken.

Discussing Continuous And Discrete

The WG discussed the continuous nature of physical quantities relevant to describing phenomena, whether extensive or intensive. However, it has become evident that a measurement criterion must be established to measure a continuous structure by prescribing *discretisation operations* that impose on the acknowledged continuous variable a structure isomorphic to that of the integers. In experimental practice, this is equivalent to the apparent fact that any measurement process will assign the same number to values of the variable that, through more refined comparisons, can be recognised as distinct from one another. In any case, the specification of an *extensive variable* in a system can always be approximated as closely as desired with an integer number. On the contrary, an *intensive variable* cannot be measured by comparing it with an integer number of repeatedly taken unit systems. To assign numbers (integer or rational) even to *intensive variables*, it is necessary to resort to transduction processes by which changes in an intensive variable (for example, the temperature of a system) systematically correspond to changes in a particular extensive variable (for example, the volume of liquid enclosed in a thermometer at thermal equilibrium with the system under investigation). From the discussion and manipulation of measuring instruments present during the meetings, it emerged that measurements of *intensive variables* by transduction systems are omnipresent in our daily technology.

Discussing Analogue And Digital

Transduction and measurement also prompted the WG to discuss the relationship between *analogue* and *digital* signals in measuring instruments. Within the study of technological devices, the term 'analogue' refers to a device that operates on physical quantities—whether electrical, mechanical, or of another nature—that, by *analogy*, represent the characteristic quantities of the system under examination. This implies a connection between two physical phenomena of differing natures, allowing identical equations to link the quantities relevant to each; thus, complex phenomena can be studied using models built from simpler phenomena. The key aspect of analogue devices was explored, which analyse the input signal in its original form by

leveraging phenomena and mechanisms within the instrument that correspond to the signal's nature. In other words, an analogue instrument distinguishes itself from a digital instrument by the absence of an additional processing phase of the input signal, known as the digitalisation phase. Once this framework has been clarified and agreed upon, a beneficial exercise is to apply it to the measurement process of a specific machine.

Discussion

Adopting a transduction perspective in physics and mathematics education necessitates rethinking physics's fundamental and epistemological elements to generate new insights for teaching and learning physics and mathematics, as illustrated by two cross-disciplinary discussions on the relationships between analogue-digital and discrete-continuous. Furthermore, the training model implemented appears convincing based on teachers' responses. Specifically, it was observed that teachers who participated in the training tended to question their own teaching models, enhancing them through theoretical reflections and the teaching materials they produced. The report presents the testimony of a teacher who argues for structural interventions to promote synergy among the disciplines.

> [...] it seems clear to us that any didactic revolution, in this case of Physics and Mathematics, cannot occur solely within the action of the individual teacher but must necessarily be supported and supported over time by the school institution. This should be translated into a systematic dialogue between the disciplines that contribute to achieving the objective.

The hypothesis is that these two scientific practices, transduction and measurement, form an ideal educational alliance for overcoming the difficulties of separation associated with the formalism of mathematical entities and the modelling of physical phenomena. It was shown that adopting a transduction perspective on phenomena requires rethinking the fundamental and epistemological elements of physics and mathematics. Incorporating daily physical experiences in concept construction is also crucial (Artiano & Balzano, 2024), and using specific measuring instruments for physical quantities, both analogue and digital, as cultural artefacts (Bussi & Mariotti, 2008) can significantly facilitate the meaning-making process, promoting multimodal reasoning and problem-solving activities (Guidoni et al., 2005b; Yeo & Nielsen, 2020).

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BioMimiCreate: Developing Creativity Through Biomimicry In Science Education In Primary And Lower Secondary Schools

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Creativity is a highly valued trait in society and has been shown to require training, as it is often schooled out of children. The focus of this article is to investigate whether biomimicry can support both the academic and creative development of primary and lower secondary school students. The study involved an interview with Søren Hansen and two trials conducted in 6th and 9th grade. The results showed that students utilized their creativity through associative thinking and that classroom culture, along with the associated psychological safety, influences their ability to apply their creative skills. Creativity can be trained through the use of biomimicry in science education.

Keywords: Classroom Implementation, Future-Oriented Science Education, Teaching Materials.

Introduction

Creativity researcher Sir Ken Robinson emphasized in a popular 2006 TED Talk that children are schooled out of creativity (Robinson, 2006). Likewise, Lene Tanggaard (2014) underscores that children possess an innate creative potential, which they use spontaneously when they play. However, this form of creativity is rarely useful or valuable in itself, but it can be developed through time, effort, and practice. Creativity constitutes an essential capacity that humans draw upon when solving everyday problems (Tanggaard, 2014). It is therefore clearly reflected in central governance documents in Denmark, for example in the Danish Public School Act, §1, subsection 2: "…the pupils develop cognition and imagination…" (Folkeskoleloven, 2022, §1, own translation), as well in the cross-curricular theme "entrepreneurship and innovation" in all national curricula in Denmark (Børne- og Undervisningsministeriet, 2019a). Furthermore, creativity and problem-solving are highlighted as important cognitive competencies in the "Education 2030" report for OECD countries (OECD, 2019; Hansen & Christensen, 2021). Finally, creativity is an indispensable element of innovation competence, one of the 21st-century skills intended to enable pupils to solve authentic problems (Dyrendom, 2016).

There are many ways to combine creativity and science. One example is Alfred Wegener's development of the theory of continental drift, and Ernst Haeckel's scientific illustrations, which are today recognized as artistic works (Østergaard, 2017). Science concerns nature and its laws (Den Danske Ordbog, n.d., own translation). By examining the principles underlying nature's solutions, human challenges may be addressed in similar ways, as both humans and nature are subject to the same physical laws and constraints. Through the deliberate inspiration from and imitation of nature's principles, sustainable solutions to human challenges or improvements to human living conditions may be developed. This approach is referred to as biomimetics or bionics (Wolfstirn, 2017), and this article examines how biomimetics can promote the development of creativity in compulsory schooling.

Research Question

How can biomimetic activities support the development of students' creativity and subject-specific learning in science education in primary and lower secondary school?

Theory

The research question is grounded in two key concepts: biomimetics and creativity. These will

be elaborated in the following sections.

Creativity

There are many different understandings of creativity, depending on whether it is viewed as context-based or as an individual competence or trait. The word *creative* is derived from the Latin *creare*, meaning "to create" (Dansk Fremmedordbog, 2024). Hansen and Byrge (2015) define creativity as a personal characteristic, centred on the ability to use one's existing knowledge in new contexts. This study adopts Hansen and Byrge's definition.

Our brains perform a cognitive process that occurs through associations every time we think. Studies have shown that individuals with high levels of creativity possess a more flexible semantic memory network. Creative individuals are generally more associative in their thinking because they are better at generating ideas, stronger in producing associative responses, and more inclined to connect highly diverse associations (Christensen & Hansen, 2015). There are two central types of knowledge within creativity: horizontal knowledge (experienced knowledge) and vertical knowledge (disciplinary knowledge). A creative person is skilled at using both horizontal and vertical knowledge simultaneously, whereas individuals who rely primarily on vertical knowledge tend to appear less creative (Hansen & Byrge, 2015).

In relation to the concept of creativity, two additional thinking processes are often mentioned: divergent and convergent thinking (McCuen, 2023). Individuals who use divergent thinking frequently produce abstract ideas. Convergent thinking processes these abstract ideas using existing knowledge and evaluates them in order to produce a realistic solution. Both divergent and convergent thinking require critical thinking, but while divergent thinking focuses on idea generation, convergent thinking focuses on forming solutions (McCuen, 2023).

Biomimetics

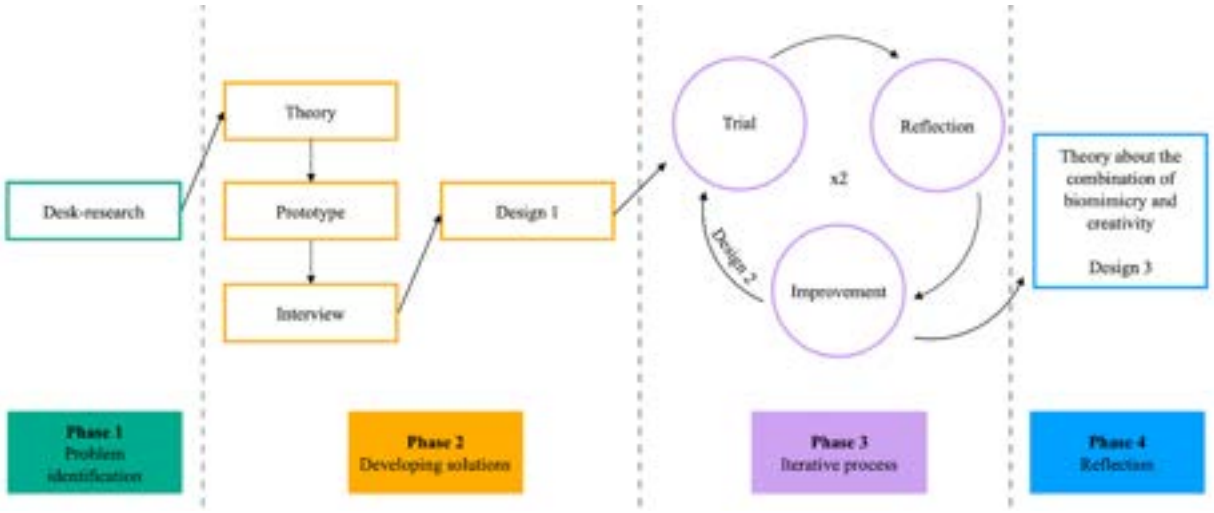
The word *biomimetics* derives from the Greek *bios*, meaning "life," and *mimesis*, meaning "imitation." Together, the term refers to the "imitation of life." Biomimetics is a relatively new multidisciplinary field, introduced in 1997 by biologist Janine Benyus. Within biomimetics, nature's forms, principles, and systems are studied with the aim of learning to draw inspiration from nature in order to develop sustainable design solutions and technologies (Coban & Coştu, 2023; Benyus, 2002).

However, one may argue that biomimetics rests on a twofold foundational knowledge. One part is the deep understanding of biological systems, and the other is the ability to transfer this knowledge to application in an appropriate manner (Jacobs & Wanieck, 2022). Within the biomimetics literature, two models of biomimetic methodology appear frequently. Although these models have different names and consist of different phases, their general structure is similar: The first is problem-driven, beginning with the identification of a problem outside biology, followed by searching for a solution within the biological domain. The second is solution-driven, beginning instead with an understanding of how a problem is solved in biology, and then searching for an application outside biology (Coban & Coştu, 2023; Jacobs & Wanieck, 2022; Gencer et al., 2020; Macnab, 2012).

Method

To investigate whether biomimetic activities support creativity and subject-specific knowledge in science, a series of activities have been developed based on theory and interviews. The entire research process is design-based and is illustrated in Figure 1. The model is inspired by the ELYK innovation model and reflects its phases (Christensen et al., 2012).

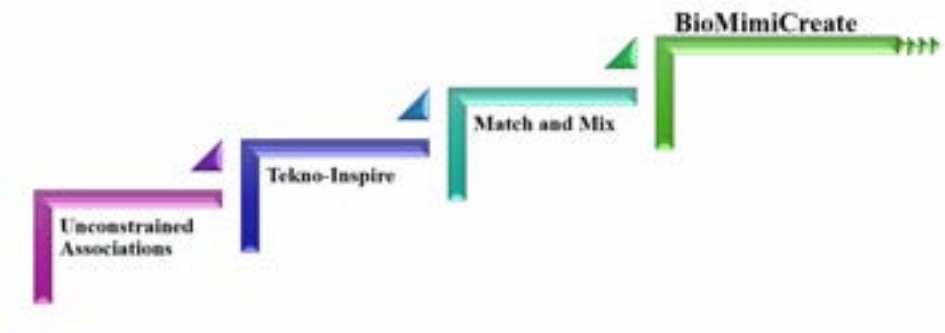
Figure 1. Process model illustrating the design of the study.



In Phase 1, the problem was identified through desk-research, which drew on previous experiences and research on creativity, the school system's frameworks, as well as literature on creativity and biomimicry. The development of the activities took place in Phase 2, where a theoretical literature search on ERIC and a semi-structured interview with Søren Hansen formed the basis of Design 1. Phase 3 consisted of an iterative process, where two trials were conducted in a 9th and 6th grade class in Denmark. After each trial, changes were made to the activities, leading to Design 2 and 3, respectively. Phase 4 involved analysis and discussion of the data and theory to arrive at a general description of the contribution of biomimicry to students' academic and creative development in primary and lower secondary education.

Creativity-Developing Biomimetic Activities

Figure 2. Progression for performing the activities. The first three activities are preparatory for the actual problem-solving game.

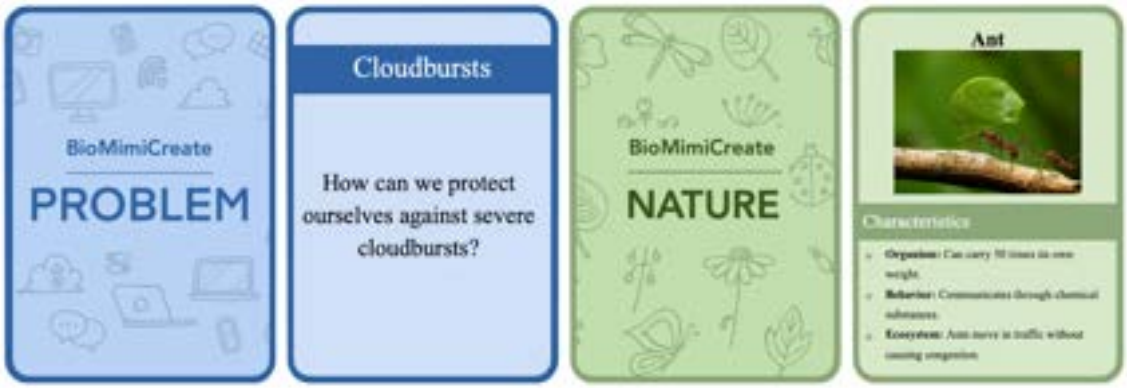


Four activities have been developed: Unconstrained Associations, Techno-Inspire, Match and Mix, and BioMimiCreate, with increasing levels of complexity. The progression of the activities is illustrated in Figure 2 above. The first three activities are warm-up exercises, aiming to create a space where students experience that there is room for free thinking and failure. Through these warm-up activities, their thought patterns and understanding of biomimicry are opened up, which is necessary when working with the BioMimiCreate problem-solving game.

The BioMimiCreate game is a problem-solving game where students engage in the development of biomimetic technologies to solve societal challenges. The game is built freely on the Creative Platform Learning (CPL) which involves four principles: uninhibited application of knowledge, task focus, parallel thinking and no judgment (Christensen & Hansen, 2015).

The cards consist of various animals with their corresponding properties and ensure that students have a knowledge base about nature, which they can use for inspiration. Based on the trials, adjustments have been made to the BioMimiCreate game, along with scaffolding sheets that make it easier to work with in practice. The latest version of the cards (Design 3) ensures that students can go through three biomimetic levels of complexity: Organism, Behavior, and Ecosystem (Gencer et al., 2020; Qureshi, 2022). Examples of the cards can be seen in Figure 3.

Figure 3. Example of problem and nature cards in the BioMimiCreate.



Analysis And Discussion

In this study, three analyses were conducted, all aimed at supporting and expanding the understanding of the relationship between biomimetics and creativity. First, a situational analysis of the practical trials (6th and 9th grade) was carried out, based on Clarke's (2003) method for situational analysis, which examines the social relations among actors, individual students' self-esteem, status, and sense of security, as well as the surroundings and conditions in the learning environment that influence students' participation in and execution of the activities. Next, an analysis of the student products from the trials was conducted and evaluated according to the three hierarchical levels of biomimetics: organism, behaviour, and ecosystem (Gencer et al., 2020). The results of these two analyses were compared with a deductive analysis of the concepts of biomimetics and creativity. The results of the analysis are presented below.

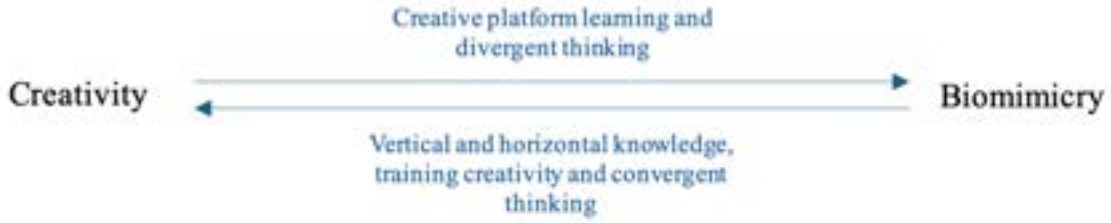
The findings showed that biomimetics draws on both horizontal and vertical knowledge, as it is a field that sources inspiration from two worlds: the technological and the biological (Jacobs & Wanieck, 2022). When new ideas emerge, existing knowledge is used in new ways through a series of associations, bringing horizontal knowledge into play (Hansen & Byrge, 2015). In biomimetic work, observations and experiences of technology and nature are used, where horizontal knowledge arises when technology is applied in practice and when nature is encountered and explored. In addition to this experiential horizontal knowledge, students acquire vertical knowledge, theory, and practice about nature and technology through the school system (Børne- og Undervisningsministeriet, 2019b). Biomimetic work draws on disciplinary knowledge about nature's forms, principles, and systems (Coban & Coştu, 2023; Benyus, 2002), which then serves as a basis for developing new technologies—requiring both disciplinary and practical knowledge of technology. This means that biomimetic work uses both horizontal and vertical knowledge, which, according to Hansen & Byrge (2015), constitutes a more advanced creative process.

According to Runco and Acar (2012), creativity is linked to divergent thinking, as it involves producing many ideas and contains an imaginative element. This is also the case in idea generation within biomimetics (Macnab, 2012). Biomimetic work aims to develop usable

sustainable solutions to societal problems (Coban & Coştu, 2023; Benyus, 2002). This presupposes that students engaging in biomimetic work are able to carry out convergent thinking, in which imaginative thinking is combined with factual knowledge in order to arrive at a realistic solution. This led to the development of Figure 4, which illustrates the combination of creativity and biomimetics.

Figure 4 visualises that creativity supports biomimetic work processes and activities through the creative platform, which helps create the conditions necessary for the development of creativity as well as for biomimetic ideas and products. Creativity contributes to divergent thinking, which is needed in biomimetic work during idea generation. On the right side of Figure 4, it is illustrated that biomimetic teaching supports creativity through creativity training, which in our case occurred through biomimetic games and activities. Furthermore, the figure shows that biomimetic work requires the simultaneous use of vertical and horizontal knowledge, which, according to Hansen & Byrge (2015), is significant for creative work. Additionally, biomimetics supplements divergent thinking by being solution-oriented, thereby bringing convergent thinking into play (Hansen & Byrge, 2015).

Figure 4. The model illustrates the interaction between creativity and biomimetic work.



The results of the trials showed that students in 9th grade draw on various disciplinary competences from the science subjects and incorporate them into their products while also applying the disciplinary knowledge from the cards. In 6th grade, the cards were the only source of disciplinary knowledge. The students' products were evaluated according to the three biomimetic levels: organism, behaviour, and ecosystem. Three out of five groups in 9th grade achieved the second level, behaviour, while the remaining two groups were at the first level, organism. All groups in 6th grade developed ideas at the organism level. These results indicate that students' creativity can be trained in both middle school and lower secondary through biomimetics, while also contributing to the development of subject-specific knowledge. The use of the creative platform can support students' creative work. In the development of *BioMimiCreate* and the accompanying scaffolding sheets, task focus and parallel thinking were incorporated, whereas unrestricted knowledge and no judgement are principles that the teacher must ensure by, for example, establishing a psychologically safe classroom culture through classroom management (Mills & Watson, 2021). The two classes that participated in the study had different preconditions for participation. One class came from an average Danish public school with 28 students, while the other class, consisting of 16 students, attended a private school that prioritises practical–aesthetic subjects. This class had, among other things, received instruction in drama, visual arts, and music throughout their schooling. The trial in 6th grade was problematic and affected by poor relationships among students and insufficient classroom management. This highlighted the crucial role of psychological safety in creativity-developing teaching (Sacramento et al., 2023; Bornemisza, 2013).

Creative Potential In Lower Secondary Students

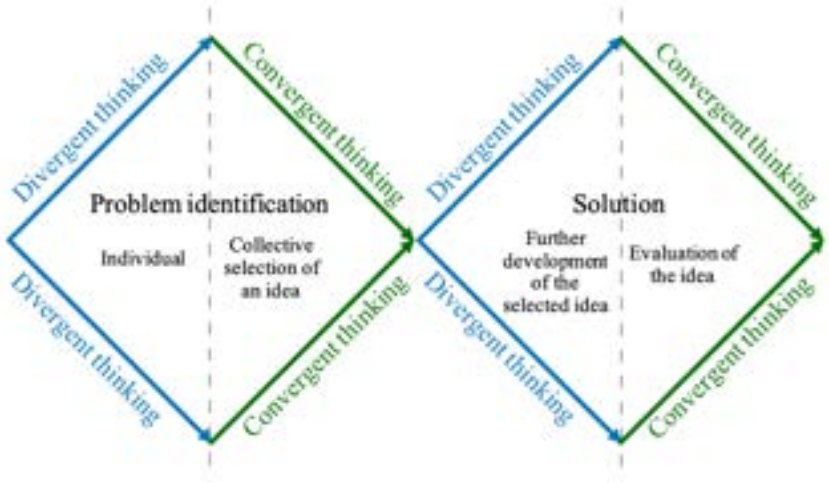
Students' creative abilities must not be lost, and therefore the school system needs to move away from a "right-answer" pedagogy in which only the responses, behaviours, and writing styles

accepted within the academic environment are recognised as correct. Such an approach blocks independent, unconventional, and exploratory thinking (Tanggaard, 2014; Hansen & Christensen, 2021).

Hansen and Byrge (2015) define creativity as a personal trait that involves using one's essential knowledge in new contexts. Through human biological development, individuals expand their knowledge both through education and lived experience. This results in a broader body of knowledge—referred to as a cognitive library—which they can draw upon when working creatively. It is therefore evident that students' creativity should be trained in the intermediate and lower secondary years, when their knowledge base is greater and can be applied in creative work. In this way, their creative abilities are not lost. This aligns with the theory of vertical and horizontal knowledge, both of which must be present in creative thinking (Hansen & Byrge, 2015). According to this theory, older schoolchildren have greater potential for valuable and useful creativity than younger children. However, this requires the presence of a creativity-enhancing learning environment with time, effort, and opportunities for practice, in which students can train and make use of their creativity (Tanggaard, 2014; Christensen & Hansen, 2015).

BioMimiCreate Trains Students' Creativity

Figure 5. Work in BioMimiCreate placed within a model of divergent and convergent thinking.



The purpose of the game is to train and develop students' creativity. At the beginning of the game, students use their divergent thinking, as they are given time to think abstractly and generate ideas individually. As they continue working, they move towards convergent thinking, where they analyse the ideas collaboratively and select one to pursue. With the selected idea, students once again think abstractly, drawing on divergent thinking as they expand the idea using additional nature cards. When students begin to assess the advantages and disadvantages of the idea, they are engaged in convergent thinking. Thus, the game explicitly supports these modes of thinking, which are essential in creative work processes. Inspired by EMU Redaktion (2022), the process described above is illustrated in Figure 5.

Grounded in the structure of design-based inquiry, we have used qualitative investigations to develop an understanding of how BioMimiCreate can strengthen creativity in compulsory schooling. The qualitative studies conducted in connection with this project are context-dependent, which is reflected in the substantial variations in the results (Tanggaard & Brinkmann,

2025). During the project, it was only possible to investigate two classes through a limited time period, making the situation one of limited observations. Generalisation is therefore not possible, but tendencies can be identified. Further research that draws on both qualitative and quantitative data is therefore necessary to confirm the potential of biomimetics to support and develop pupils' creativity in primary education. Creativity proves difficult to measure quantitatively, but one of the most widely used assessments is the Torrance Test, which is based on four criteria: fluency, flexibility, originality, and elaboration (Torrance, 2018). This test was attempted during the trials, but due to environmental disturbances and insufficient time, the results were inconclusive, and the test outcomes are therefore not included in this article.

Conclusion

The work shows that biomimetics in science education at the primary school level develops both creativity and subject-specific learning. Using CPL as the framework for the biomimetic work helps to create the right conditions for the development and training of creativity, as well as the development of biomimetic ideas and products. In this way, students' creativity is developed through biomimicry by using creative thinking processes. Subject-specific knowledge is developed through biomimicry as students draw on existing and new knowledge to create biomimetic products that can solve societal challenges in a sustainable way.

Reflections

A further line of work with biomimetics and creativity would be to examine their relationship with innovation and the Engineering Design Process (EDP). Both fields involve problem solving, systems thinking, and creativity (Qureshi, 2022; Auener et al., 2022). According to Bemiss (2021), innovation is the ability to adapt an idea through creativity so that it solves a problem and creates value for others. Innovation cannot occur without creativity, whereas creativity can be exercised without necessarily leading to innovation. Creativity enables individuals to use their existing knowledge to see new connections and generate ideas, while innovation builds on these creative ideas by putting them into action, bringing them into the world, and solving problems (Tøttrup, 2023; Designovations Knowledge Articles, 2023; Bemiss, 2021). Bemiss (2021) further argues that innovation should be experienced from early childhood, as children then develop innovative mental schemas that they will draw upon throughout their lives. This is illustrated as follows:

Figure 6. **The figure illustrates the combination of creativity and biomimetic work.**

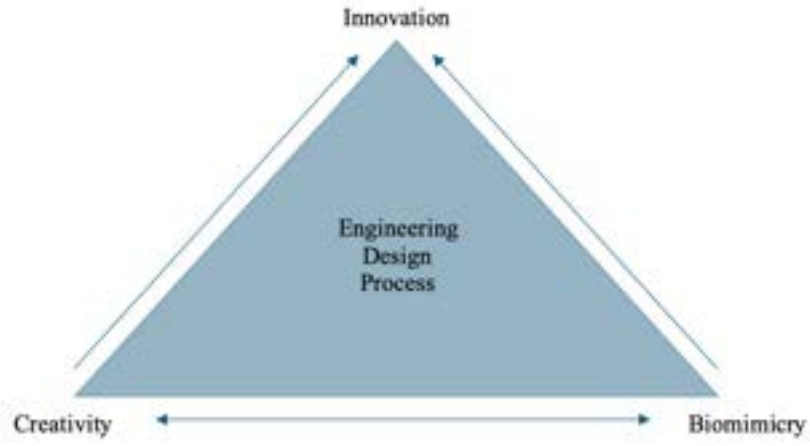


Figure 6 is based on Figure 5, with engineering added as an inner layer of the triangle, functioning as a working method that connects creativity, biomimetics, and innovation.

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ESERA 2025 Copenhagen

"Antena Cultural": Podcast As An Educational Tool For Scientific Dissemination Of Amazonian Insect Biodiversity

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Brazil is the country with the greatest diversity of insects, and much of it is still unknown. Therefore, biodiversity research is important, including for its conservation. One of the projects related to this objective is BioInsecta, which attempts to understand the patterns of vertical distribution of insect biodiversity in the Central Amazon rainforest. In other words, it tries to understand the distribution of the various guilds of insects at different heights in the forest. The project also impacts education beyond science. People's distance from nature has generated a negative perception of insects that must be combated through adequate scientific education. This education must also be culturally contextualized since insects are part of the history and identity of many ethnic groups. Besides, people are rarely sensitized only through science - the favorable feeling comes from this cultural representation. Deconstructing the negative image of these animals must be done inside and outside the classroom, which is why knowledge must be available on digital media and schools must take advantage of these technological tools. In an attempt to reconstruct knowledge about the biodiversity of insects in the Amazon within this cultural context, the Antena Cultural podcast arose as part of the BioInsecta project to connect science and culture educationally. This article describes the creation of the podcast, its central concept, its structure, its products, and its potential for education, while also explaining the next steps of the project.

Keywords: Insect biodiversity, science education, podcast.

Introduction

Insects are part of the largest and most diverse terrestrial multicellular organisms' group on the planet (Lewinsohn *et al*., 2012, p. 1) and Brazil has the highest insect diversity (Rafael *et al*., 2009). Furthermore, the number of existing species is much greater than the species already known, giving great importance to research projects on this biodiversity — and its conservation. One of the projects related to this objective is BioInsecta (https://bioinsecta.org/), which attempts to understand the patterns of vertical distribution of insect biodiversity in the Central Amazon rainforest. In other words, what is the distribution of the various guilds of insects at different heights in the forest: some species live exclusively on the ground, others only in the canopy, and others move at different heights.

This project also impacts education. Rapid urbanization has distanced people from natural environments (Silva & Sammarco, 2015), generating a largely negative perception of insects (Albuquerque *et al*., 2022). This perception, reinforced by the media, common knowledge and even at school, must be restructured through adequate science education (Trindade *et al*., 2012) and culturally contextualized. Although scientific knowledge is fundamental, it hardly generates sensitivity in people towards nature (Fernandes-Pinto, 2017). Insects in different cultures represent part of their history and identity. Education, which also plays a role in conservation through the development of new behaviors towards the world, must incorporate and value this rich part of the culture as much as it exalts textbooks.

Thus, deconstructing prejudices against insects is an essential role of schools, but it is not limited to them. Likewise, schools must use other available tools to make teaching more dynamic. In an attempt to reconstruct knowledge about the biodiversity of insects in the Amazon within this

cultural context, the Antena Cultural podcast (https://open.spotify.com/show/5uTbwtehzLac2YPWCzosuy?si=caa8ab8c604e428f) arose as part of the BioInsecta project to connect science and culture educationally. This article describes the creation of the podcast, its central concept, its structure, its products so far, and its potential for education, while also explaining the next steps of the project.

Methodology

The Antena Cultural concept emerged over six months of weekly meetings and fieldwork during the second half of 2024. Once defined the project's goal (to disclose the scientific advances of BioInsecta and transform the generally negative view that people have of insects), it was necessary to choose the media format, the target audience and the structure of the episodes.

Through fieldwork (interviews with residents of Manaus and Ribeirão Preto) and bibliographical research on the general perceptions of insects, it became clear that, for the project to achieve its objective, it should adopt a flexible, dynamic vehicle of communication with a good audience reach, a relaxed but scientifically accurate language, and a narrative that allowed people to identify with the topics addressed. Podcasts have been seen as a media capable of reaching different audiences, initiating new trends and helping to democratize information (Games, 2021). Not surprisingly, the production and consumption of podcasts have increased, including in Brazil (Games, 2021). Thereupon, it was the chosen vehicle.

Parallelly, the target audience chosen was young adults. The podcast presenters were undergraduate students of Biology and fit into this age group. The podcast, which follows a casual conversational tone, with the students sharing their experiences, adopts the same language used in everyday life. Considering the public, a strictly scientific appeal in the narrative couldn't generate the expected engagement. The theme had to be introduced through emotions and knowledge that could be recognized by the audience. Fear, apprehension or disgust, but sometimes also amazement, admiration and affection, are common feelings for people towards insects, so the narratives should start from this point.

Regarding science, based on people's perceptions, the insects to be covered in the episodes should be contextualized from the point of view of an expert to avoid misunderstandings and the dissemination of distorted information. At the same time, the explanations should not be too complex for the lay public to understand: the expert should communicate effectively. Before being studied by science, insects were already part of the beliefs and history of various ethnic groups. These animals were part of their cuisine, medicine, art, literature, cosmogonies and superstitions. Therefore, the idea was to also bring back these representations, showing that negative feelings towards insects have not always predominated or do not apply to all groups and that these animals also have historical and cultural value. It would allow listeners to come across another logic of the world, reflect on their perceptions and feel more empathy towards this gigantic and diverse group of animals.

Considering all these aspects, it was decided that, once the theme of the episode was chosen, the scripts for the episodes would follow three main lines:

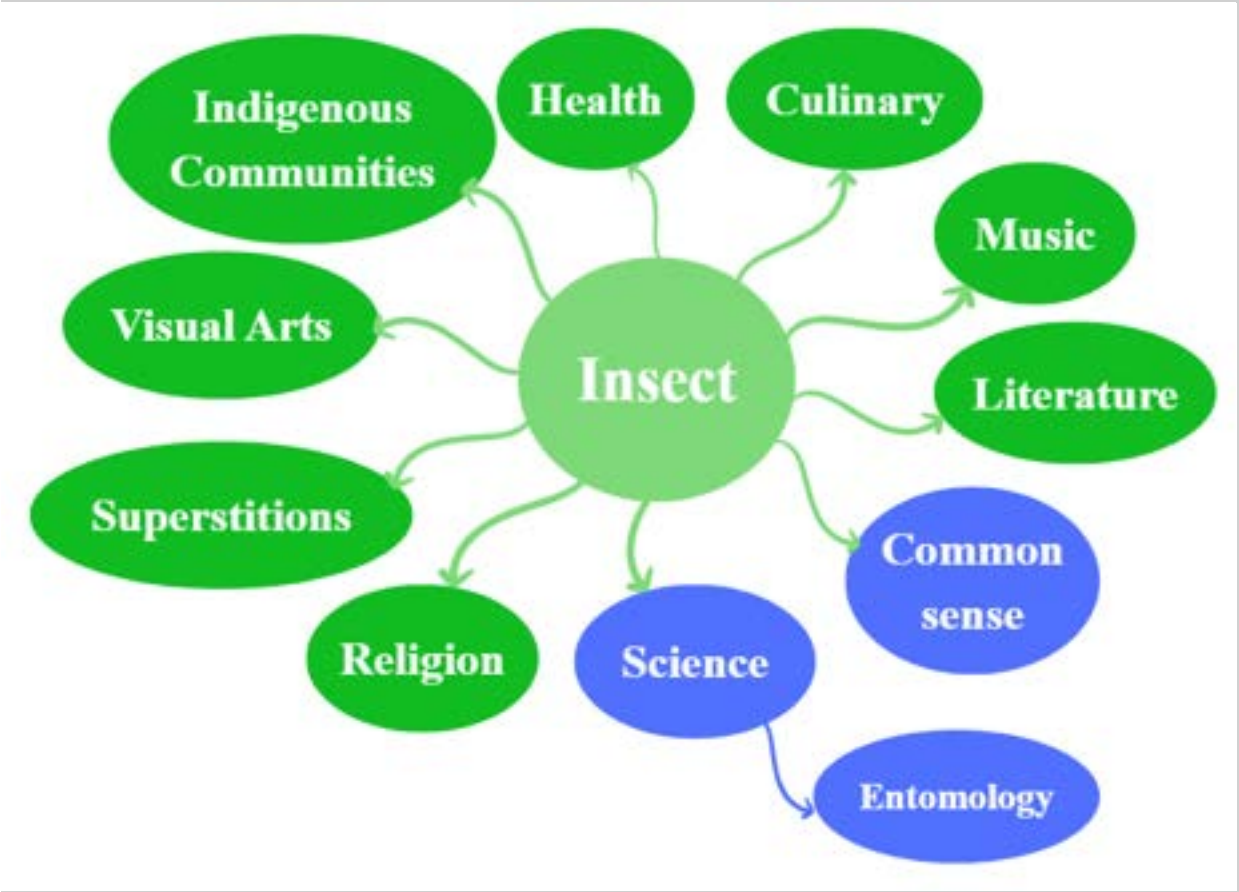
1. Common sense: we would identify how much people know about the insect chosen for each episode, and their feelings and memories towards the animal. The episodes could bring statements from ordinary people obtained through interviews conducted in Ribeirão Preto, Manaus or through some other means of communication;
2. Explanation from an expert: an entomologist, a specialist in the chosen insect, would be invited to provide a brief definition of what the insect is like, its most common

characteristics, and interesting facts related to the animal (according to the episode's theme);

3. Addressing culture: insects would also be remembered as part of the culture through discussions about how important it is for an ethnic group, its relevance to art, cuisine, superstitions or religion, for example. Furthermore, a social issue could be addressed together, such as prejudice towards Brazilian Indigenous culture or gender matters.

For the creation of the episodes, we first defined the theme, conducted all the interviews, analysed them, and then wrote the final script, selecting which parts of each interview would be included in the final audio. The scripts were divided into frames, and each segment featured dialogue from the presenters and interviews with guests (insect experts, artists, the general public, etc.). The script outline, therefore, would be:

Figure 1. Antena Cultural script outline. First, the episode's theme (or insect) is defined, which will be explored from a scientific perspective alongside common sense, and then some sub-themes from the cultural axis are chosen for discussion.

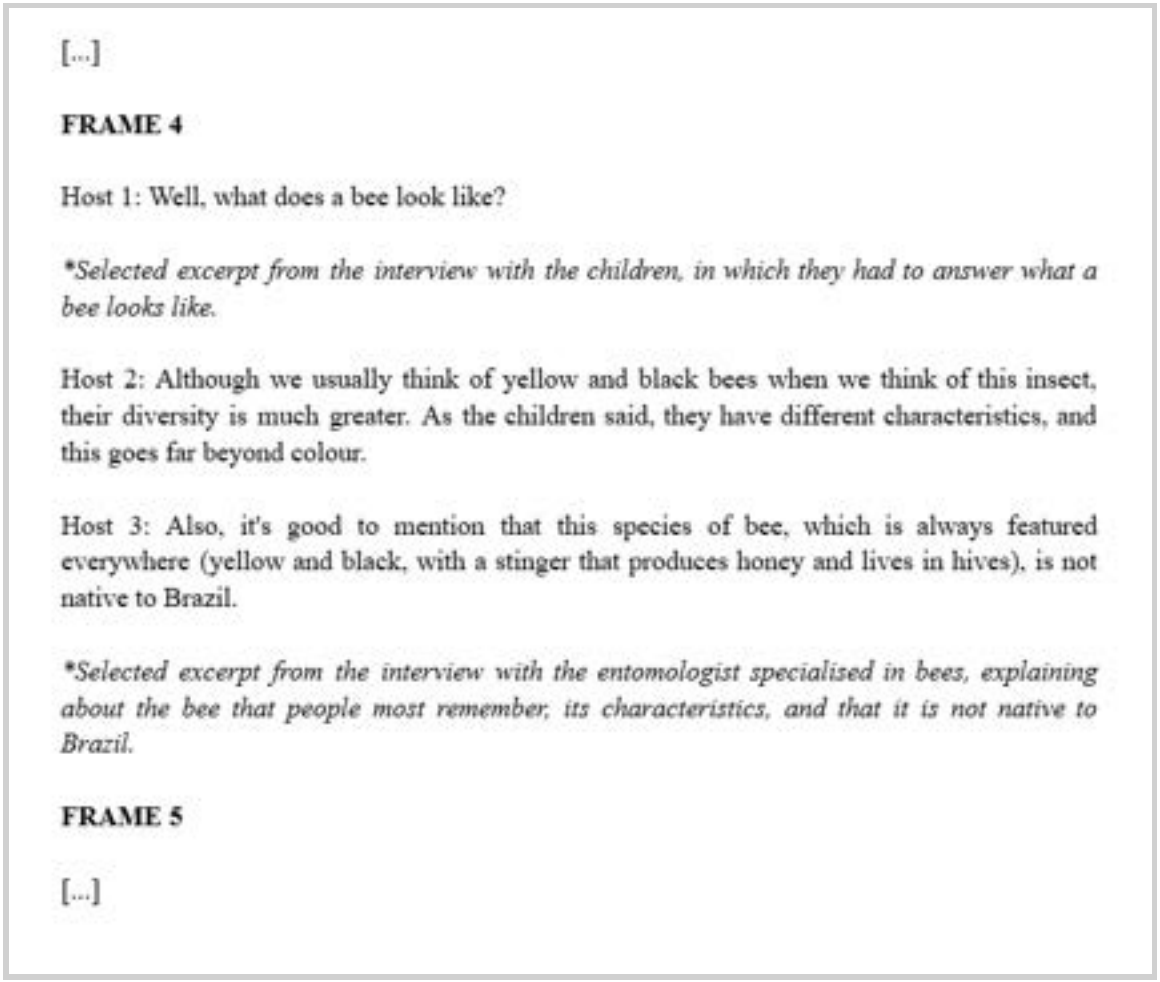


After this phase, the hosts would record the narration, insert the interviews and edit the episodes using tools such as the Audacity program.

Results

The creation of this podcast resulted in 7 episodes so far, and they started to be published in June, 2025. Some episodes aimed to discuss the BioInsecta project specifically, its research members, and introduce Antena Cultural as its scientific outreach hub. Others developed from the choice of a well-known insect. Two episodes chose to focus on important dates in Brazil, such as Children's Day and Christmas.

Figure 2. A part of the script of the fifth episode translated as an example of how it looked. Each episode would follow this structure: 1) define the theme and the subtopics, 2) collect interviews, 3) analyse the interviews, 4) write the final script, always alternating between the hosts' speeches and those of the interviewees in each frame.



[...]

FRAME 4

Host 1: Well, what does a bee look like?

**Selected excerpt from the interview with the children, in which they had to answer what a bee looks like.*

Host 2: Although we usually think of yellow and black bees when we think of this insect, their diversity is much greater. As the children said, they have different characteristics, and this goes far beyond colour.

Host 3: Also, it's good to mention that this species of bee, which is always featured everywhere (yellow and black, with a stinger that produces honey and lives in hives), is not native to Brazil.

**Selected excerpt from the interview with the entomologist specialised in bees, explaining about the bee that people most remember, its characteristics, and that it is not native to Brazil.*

FRAME 5

[...]

Table 1. Antena Cultural released episodes and their respective themes. The titles of the episodes are translated, as the episodes are written and recorded in Portuguese.

Episodes titles	Theme of the episode
Episode 1: Amazon	The first episode was introductory, without focusing on a specific insect. The interviews with the audience showed some Manaus residents' perceptions of insects. The scientists interviewed talked about the project itself and their motivations for enjoying working with science. The last interviewee was an Indigenous nutritionist from the Sateré-Mawé ethnic group, who spoke about the importance that the leaf-cutter ant has for her culture, for example, and about the prejudice of outsiders towards her community's diet.
Episode 2: Ants	The second episode was about ants. The interviewees shared their perception of ants as pests and admiration for their social behavior. The specialist explained what ants are, what differentiates them from other insects, the variety of existing species, and their ecological role. In the last segment, an anthropologist from the Sateré-Mawé ethnic group spoke about eating ants as a social practice and their importance as a symbol of the transition to adulthood. The episode ended with the

	interviewee from episode 1 commenting on the proven nutritional value of leaf-cutter ants according to science.
Episode 3: Butterflies	The third episode begins with the narrative of Iansã, a warrior deity of Candomblé and Umbanda, who can transform into a butterfly. Through this narrative, our own capacity for transformation throughout life was discussed, how changes require patience and reflection, and how we should allow ourselves to feel emotions deeply to become more mature. A parallel was drawn with the metamorphosis of butterflies. An entomologist specialist in these insects explained what butterflies are like, how they change from an egg to a butterfly, why they are so colorful, and their function as pollinators and environmental indicators.
Episode 4: Bioinsecta	The fourth episode is specifically dedicated to better explaining Bioinsecta. It begins with a conversation about the importance of curiosity in biology and develops to discuss what Bioinsecta proposes, its hypotheses, the methodologies used, and how fieldwork and laboratory work are conducted. All interviewees were scientists who are part of the project. Furthermore, the episode also discusses the importance of people and their life experiences in the construction of science, and that practicing it also requires a great deal of love for what is studied.
Episode 5: Bees	The fifth episode was a tribute to Children's Day and included interviews conducted with children at a daycare center located within the University of São Paulo, called Creche Carochinha (https://www.instagram.com/creche_carochinhausp.rp/). The presenters began by sharing stories from their childhoods, what they liked to play with, and introduced the scientists, who commented on what bees are, their colors, their life habits, their evolutionary process, and their ability to play. They explained that there are studies about the ability of these insects to play for pleasure, that bees are quite intelligent and that their play helps in their development. From this, the presenters make a connection to the importance of play for child development, the history of early childhood education in Brazil, and extend an invitation for people, even adults, to engage in play.
Episode 6: Women in Science	The sixth episode was made to honor Brazilian women scientists. It explored the stories of important Brazilian scientists, especially in the field of biology. Interviews were conducted with entomologists who opened up about their stories, their careers, the difficulties of entering and remaining as researchers, the reasons that led them to become scientists, and their future perspectives.
Episode 7: Katydid	The theme of the last episode was hope (in Brazil, katydids are known as "esperança," which means hope in Portuguese). The purpose was to create something inspiring, considering the end-of-year holidays (like Christmas), and at the same time informative, playing with the double meaning of the term "esperança." The episode featured

interviews with people who explained what hope meant to them, what they expect from the future, and why they think the insect is also called "esperança". The researcher interviewed explained about this group of insects, their most common characteristics, and where the name came from.

Discussion And Conclusion

Insects are essential ecologically and economically (Trindade *et al*., 2012) and are part of the culture of many people. Records show a historically peaceful and beneficial coexistence with these animals (Albuquerque *et al*., 2022, p. 119) and they are known in literature, language and music, visual arts, cinema, theatre, cuisine, medicine, religion and recreational processes in different societies — past and contemporary (Costa-Neto, 2002 as cited in Trindade *et al*., 2012, p. 38). There is a long list of reasons for an effort to conserve the enormous biodiversity of insects. Combining science and culture is an effective path.

Raising awareness of the importance of conservation through education is particularly powerful. To overcome prejudice against insects the approach must move away from practices essentially centred on classifications and memorization of scientific terms - a reductionist, fragmented and inefficient view (Amorim *et al*., 1999 as cited in Trindade *et al*., 2012, p. 39). “To be effective, the learning process must, first and foremost, start from an awareness of the times in which we live” (Santos, 2008, as cited in Santos & Santos, 2015, p. 308), so education must take advantage of the technologies used in everyday life. Besides, people seek information in digital media, so they also need to be there! Jesus (2014) says:

> “Education is immersed in culture and not only linked to science, which in modern times were considered the only valid sources of training and capable of offering technologies. It uses processes that construct public and shared meanings, which mediate its way of being in the environment. As this is constantly changing, the Podcast presents educational possibilities and challenges that deserve the attention of educators and researchers” (Jesus, 2014, p. 10).

Podcasts use many journalism techniques and demand research, synthesis and storytelling skills. Furthermore, the structure followed by Antena Cultural is similar to processes described by both Saviani and Vygotsky: both are concerned with not discarding the student's knowledge but rather preparing a class whose objective and methodology resemble the reality of children (Pereira *et al*., 2022). The interviews with the audience in the podcast are precisely the social practice described by Saviani (obtaining prior knowledge from the audience). Each episode ending corresponds to the final social practice (in which the agents involved transform themselves in the learning process) (Pereira *et al*., 2022).

The episodes are rich in science and culture and given their format, they can bring information to a diverse audience, including a class of students (although the target audience is young adults, the episodes can be easily understood by other age groups). Antena Cultural shows how science projects such as BioInsecta can escape the risks of generating decontextualized, boring and dissociated information from culture when sharing their results. The podcast has the potential to be an effective teaching tool; therefore, the objective of this work was to demonstrate its structure and the results of its creation. Considering its recent launch and the context in which it was created (by undergraduate students during a scientific initiation project linked to Bioinsecta), the next steps of the research will be to analyse the podcast's metrics on the platforms where it is available and to use it as teaching material in the classroom (in an inquiry didactic sequence, for example).

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Section: Embodied And Multimodal Meaning-Making To Invite Creativity And Imagination

ESERA 2025 Copenhagen

Navigating The Praxis Of Fiction & Non-fiction For Engaging With Science Through Storying

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Imagination, creativity, and emotions are essential in science work and have shaped the history and evolution of science. At the same time, they also play a vital role in engaging with, teaching, and learning science. Nevertheless, science is stereotypically still regarded as an objective set of facts and laws, continuing to highlight the divide of the mind over the body and the self. The way science is commonly presented and taught remains fragmented along disciplinary lines and decontextualized from feelings, identities, and imagination. In contrast, the arts embrace emotions and cultures in fictional and non-fictional contexts. Hence, bringing the arts into science education provides an opportunity to create innovative and engaging learning spaces and places. This symposium examines how the art forms of storying, story-(writing, telling, and performing) can be used to provide missing aspects in science education. We investigate how the creation of stories can facilitate the expression and negotiation of meanings and possible selves through fiction and non-fiction worlds. Different modes and story genres are taken into consideration, attending to stories composed in interaction with places, folklore cultures, bodies, and artefacts. The studies shared also offer guidance in developing innovative approaches to science education that make effective use of storying for communicating and negotiating meanings, emotions, and selves.

Keywords: multimodal learning; cultural diversity; equity in education

Introduction

Science is commonly perceived and taught as an objective set of facts and laws, whereas logical and paradigmatic thinking relies on data-driven correlational thinking (Bruner, 1986). On the contrary, the role of imagination and creativity in science has not received enough attention or has even been ignored, regardless of their integral role in the Nature of Science (Hadzigeorgiou, 2016). Moreover, science instruction has mostly followed the divide of the mind from the body, hence connecting knowledge construction to the mind, which appears divorced from the body, the self, and the emotions (Varelas et al., 2022). In response to the need for more informed and holistic representations of science in schools, several researchers have advocated the inclusion of the Arts in science/STEM education. The Arts can provide spaces and places for multimodal representations of ideas, can offer opportunities to share and reflect, and can support choice-making through playful ways (Varelas et al., 2022).

This symposium focuses on the various art forms of storying, such as story-(writing, telling, and performing). We define stories as narrative structures where characters interact in spacetimes with other characters/events/scenes, while the present played out in these interactions is informed

from the past, and influences what may happen in the future. Particularly, the above conceptualization of stories draws upon the use of Bakhtin's notion of chronotopes, i.e. the temporal and spatial relationships, which have been used to examine students' understandings of science and science identities through the analysis of their narratives (Varelas et al., 2012). Not only storying can help researchers gain deep insights about the participants' understandings and identities in science, but it can also help participants make sense of their own teaching and learning as well as their own selves and positionings (Chappell, 2024; Varelas et al., 2022). Furthermore, stories, both in fictional and non-fictional forms, are an effective way to understand the world and communicate understandings (Bruner, 1986) in a more approachable, sustainable, and epideictic manner (Avraamidou & Osborn, 2009).

Considering the above, the three studies included in this symposium aim to explore both theoretically and empirically the potential of storying in science education in a variety of forms and contexts. First, one study examines the use of storying in non-fiction contexts, such as the real-world problem of climate change that challenges our society and our survival, by calling upon teachers to story their understandings, critical views, and experiences. On the other hand, a pair of studies examines storying in fiction worlds, through the analysis of science fiction stories and imaginary fairytales to examine teachers' and instructional designers' use of metaphorical representations in science, sociopolitical inequities in science, and reimagined notions of the future, freed from the confines of reality. Second, the symposium papers investigate storying in diverse contexts: school students, pre-service teachers, and teacher education designers. Hence, the implementation of storying within these distinct communities aims to highlight nuances regarding their applicability and dynamics in each target group.

Third, this symposium examines the use of storying through multimodal ways, including the use of developed textual and/or visual artefacts, folklore cultural assets, and ethnical identities. Particularly, the first study developed a theoretical narrative-based framework to analyse narrative artefacts used in climate change education, as well as to analyse the narratives that school students create while reflecting on the uncertainty involved in climate change from an epistemological point of view. The second study examined the use of fictional storying i.e. fairytales for integrating early childhood curriculum content and teaching strategies such as inquiry-based learning by pre-service preschool teachers. Finally, the third study aimed to critically read and analyse existing Afrofuturistic fiction stories to identify existing normative structures in them, reflect on them, and propose informed and inclusive learning environments for teacher education designers.

An Operative Tool To Unpack The Complexity Of Narratives And Narrative Thinking For Climate Change Education

Introduction

In recent years, an increasing number of scholars has shifted attention from narratives as rhetorical or engagement devices to narratives as core cognitive structures that shape how humans understand the world and guide their action (Bruner, 1986; Norris et al., 2005; Fletcher, 2023; Soares et al., 2023). From this perspective, narratives constitute a distinct mode of thought: alongside paradigmatic thinking—characterized by abstraction, generalization, and logical-mathematical reasoning—narrative thinking organizes meaning around action, temporality, and contingency.

Although historically associated with different domains of knowledge, these two modes are not mutually exclusive. Several scientific disciplines operate at their intersection, combining law-like explanations with historically contingent processes. Natural history offers a clear example: as

Gould (2002) argued, narrative explanations are indispensable when outcomes depend on specific sequences of events and initial conditions. In such cases, explanation cannot be reduced to invariant laws alone, but must account for how things could have unfolded differently.

In Climate science, while some scientific practices aim to reduce uncertainty through prediction, climate-related questions often involve irreducible uncertainty, long temporal scales, and complex interactions between physical and social systems. In response, climate science has increasingly adopted narrative approaches—such as storylines and scenarios—to explore uncertainty, risk, and decision-relevant futures (Shepherd et al., 2019; 2021).

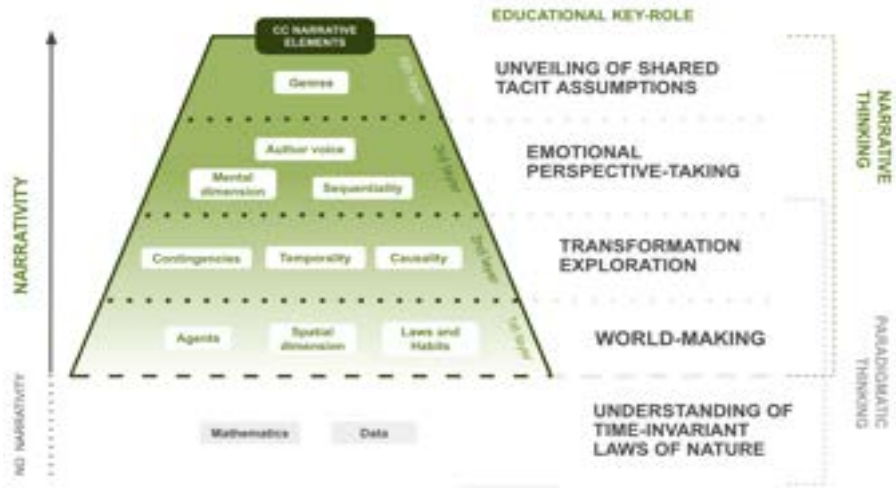
Within Climate Change Education (CCE), pairing paradigmatic with narrative thinking could offer a unique avenue for learners to grapple with Climate Change (CC) complexities and uncertainties by moving the focus from prediction to decision-making (Shepherd et al., 2021), making ethical and value-laden dimensions of climate action explicit while maintaining scientific rigor. This study starts the investigation of this issue from the following research question:

RQ) *How can we develop an operational definition of narratives for Climate Change Education purposes that is capable of unpacking narrative complexity as a mode of thought?*

Theoretical Framework and Methodological Approach

Despite their recognized relevance, narratives remain inconsistently defined across disciplines. Educational and communicative frameworks adopt definitions that range from overly broad ones—almost conflating narratives with general beliefs or perspectives—to narrow criteria that exclude scientific narrative artefacts such as scenarios and models (Bruner, 1986; Costantino & Weber, 2021). This study builds on Ryan's concept of narrativity (2005), which distinguishes between "being a narrative" and "possessing narrativity." While the former refers to artefacts explicitly designed as stories, the latter includes any artefact that enables narrative sensemaking, regardless of authorial intent. This distinction is crucial for climate education, where many epistemically relevant artefacts are not stories in a literary sense but nonetheless support narrative reasoning.

Figure 1. CC narrativity pyramid tool for CCE. This figure illustrates the multi-layered tool to analyse the relevance of CC narratives for CCE through the concept of narrativity.



Integrating Ryan's concept with Bruner's dual-mode theory, the study proposes a four-layer narrativity tool that conceptualizes narrative and paradigmatic thinking as a layered spectrum and categorizes climate-related artefacts based on the cognitive practices they afford, rather than on their medium or genre. Methodologically, this study is theoretical and conceptual. Drawing on interdisciplinary literature, it constructs and illustrates the framework called "Narrativity

Pyramid", shown in Figure 1 (D'Orto & Tasquier, 2025).

At the base of the framework are non-narrative, strictly paradigmatic artefacts, such as equations, datasets, and isolated data visualizations. These artefacts privilege abstraction and invariance and are essential for scientific reasoning, yet they offer limited support for temporal or causal sensemaking. The first layer of narrativity introduces world-making processes (Cheng, 2018), where artefacts describe spatial, systemic, or rule-based conditions governing a given reality. Examples include maps, setting descriptions, models, and representations of physical or social law systems in real case scenarios. This layer helps students in contextualizing knowledge. The second narrativity layer incorporates temporality and causality, depicting sequences of events that introduce contingency and the possibility of change. This layer includes chronicles, timelines but also scientific storytelling approaches used in climate science, such as storylines and Shared Socioeconomic Pathways (O'Neill et al., 2017), which support reasoning about alternative futures while remaining grounded in scientific plausibility. The third layer foregrounds subjective experience by introducing perspectives, intentions, and emotional dimensions. Artefacts at this level invite learners to engage with ethical questions and lived experiences, fostering empathy and reflective judgment. The fourth and last layer of narrativity concerns genre conventions, which shape how narratives are structured and interpreted within cultural contexts. Genres like "Climate fiction" and "Solarpunk" exemplify this layer, where narrative forms encode assumptions, values, and visions of social transformation (Ghosh, 2016).

Discussion

The proposed narrativity framework offers a structured approach to integrating narratives into CCE without reducing them to engagement tools. By positioning artefacts along a spectrum of paradigmatic and narrative thinking, the tool's goal is to support educators in selecting and designing materials (or just putting the focus on aspects of them) that are aligned with specific cognitive focus and educational goals. This perspective reframes narratives as cognitive artefacts that foster particular ways of reasoning, rather than as stylistic additions to scientific content.

The key strength of the framework lies in its capacity to balance analytical rigor and meaning-making: while CCE often oscillates between data-driven approaches that risk disengagement and narrative approaches that risk oversimplification, the narrativity pyramid provides a way to integrate these dimensions, ensuring that narratives remain epistemically grounded while supporting agency, ethical reflection, and future-oriented thinking. Its transmedial scope further acknowledges that narrative sensemaking can emerge across diverse formats, from scientific scenarios to literary and visual media.

While this study lays a theoretical foundation, other research has already examined the framework's application in educational settings and its impact on learning outcomes, thereby contributing to a broader understanding of how narrative and paradigmatic modes of thought can be balanced in CCE (D'Orto, 2026).

Inquiry Fairytales: Pre-Service Teachers Integrating Science And Scientific Inquiry In Fairytale-Like Stories For Science Teaching

Introduction

This study focuses on imaginary fairytales as an appropriate and common form of stories for children. Fairytales are defined as "narratives that contain improbable events, scenes, and characters and that often convey a whimsical, satirical, or moralistic theme" (Bayton, 1996). According to Propp (1968), fairytales follow a common structure depicted in a limited list of 31 narrative functions. For example, the plot includes functions such as the hero/ine's absentation, trickery from a villain, hero/ine's struggle, punishment and/or marriage, etc.

The dynamics of fairytales rely upon what Vygotsky called dialectical "relations between fantasy and concrete situations", combining fictional characters, situations, and stories with real-world phenomena (Fleer, 2015). The non-realistic nature of the characters and events allows students to freely cognitively and emotionally connect with them and debate their decisions, either justifying, rejecting, or sympathising with them (Massi & Benvenuto, 2001). However, one of the biggest shortcomings is that stories are mostly implemented through a teacher-led narration with little or no interaction from the students, which we could infer reflects rather traditional pedagogies. Contrastingly, this study proposes incorporating along the story stages of inquiry such as prompting students to make predictions, collect and analyse data, and draw inferences which would significantly affect the evolution of the story and assist the story characters in acting and making decisions. We call this participatory form of stories 'inquiry fairytales', and we hypothesise that this form can benefit and engage students in story-based approaches to science in a similar way that inquiry-based teaching does in traditional science teaching. Another challenge is that fairytales traditionally reflect cultural norms and values which are often criticised as stereotypical and non-inclusive. However, fairytales are remakes of folklore stories that keep coming up generation after generation in an endless loop. Hence, retelling fairytales in new forms has become a recent trend that has the potential to bring inclusive and diverse stories for underrepresented people (Goldman, 2023).

Considering the above, a thorough examination is needed of how appropriate and participatory fairytales can be developed by pre-service teachers. Specifically, inspecting the ways that teachers integrate science and scientific inquiry into the story and the story patterns that they tend to develop would yield insights regarding the dynamics of fairytales for science teaching.

Hence, the research questions are:

RQ1) How do pre-service teachers compose stories in the form of inquiry fairytales for science teaching?

1.1) In which narrative functions do they integrate science, and in what ways?

1.2) To what extent do they integrate stages of inquiry-based teaching, and in what ways?

Methodology

The study was carried out in the context of an undergraduate science education course at the Preschool Education department of the University of Crete. Following six weeks of theoretical lectures including inquiry-based teaching, the participants were called upon to design lesson plans and worksheets on a science topic of their choice. In the ninth week, they were introduced to using story writing for science teaching, including small-group story-writing training activities. Subsequently, each participant was called upon to develop an inquiry fairytale regarding the science topic they had previously chosen, as an optional homework essay. Data collection includes a) teachers' fairytales (n=28), and b) lesson plans and worksheets (n=21). The fairytales were qualitatively analysed concerning a) the stages of inquiry-based teaching that they implemented, b) the narrative functions (Propp, 1968) that they implemented, and c) a qualitative comparison of science topic aspects integrated into the fairytale in comparison to the lesson plans.

Findings

Science Integration In Narrative Functions

The preparatory part was mostly made through *absentation* (n=9 fairytales), *interdiction* (n=7), and *violation* of the interdiction (n=10). Science was not extensively integrated into this part apart from introducing some personifications of natural elements (e.g. droplet, cloud, ice cube) as story characters. Contrastingly, science phenomena were commonly integrated into the story through

the functions of *villainy* or *lack* (n=21). Particularly, instead of using a personified villain, teachers tended to integrate a natural phenomenon or disaster as *villainy/lack* to complicate the plot. Indicative examples are as follows: *He was looking for him [ice-cream] everywhere, and after a long search he finally found his friend who was very sick and had almost melted [T9]. Flames engulfed the kitchen curtain. The fire followed the oil spilt on the floor and reached the exit door, so there was no way out of the house [T7].*

Science was also commonly integrated in the *mediation/connective incident* (n=22). Specifically, this function was frequently actualised by the main character being called, asking help from a character's friend/parent, or seeking advice from an 'expert', who was commonly embodied through a wise owl or the hero/ine's mother. *They decided to visit the Great Tree, where the wise owl was living. She used to know everything concerning atmospheric pressure and weather cycles [T5].* Testing the character through a *struggle/fight* (n=6), *marking the hero/ine* (n=1), *difficult task* (n=5) and its *solution* (n=4) appeared as forms of the climax of the plot in which science came into play. *The Darkie asked his own subjects if they liked living in a state that always has night. All of them answered that they were bored having rest […] She [Earth] decided to spin around herself every 24h while also circling the Sun [T16].* Notably, the functions of an actual fight appeared limited and in milder forms, such as a debate between characters or a reproof. *Lily: Stop, Ben! You don't know how much harm you cause to all of us by cutting the forest trees. [T23]*

Science phenomena were also integrated through the *provision of a magical agent* (n=9), e.g. by obtaining an experimental object (e.g. rock, mirror) to be used for rescue or the evolution of the story. *While they were searching to find something that looked like a boat, suddenly, Vasiliki found a big log [T3].* At the end of the story, almost all stories had a *liquidation* of the misfortune or lack (n=24), while *marriage* appeared limited (n=2), and *punishment* of the villain was absent.

Stages Of Inquiry

A considerable number of teachers (n=13) did not implement any interactive part in their story. Nine teachers implemented inquiry questions through dialogue/questions among the plot characters, without directly engaging the students, which was coded as an implicit way of inquiry. For example, *Katia's mother asked girls "so why did the rock sink and the log floated?" The girls started saying several ideas (T3).* The most common inquiry stage explicitly implemented was the expression of ideas (n=7). *What do you think, kids? How do you say a rainbow is formed?[…]Exactly my long-reigning caliph! The colours are hidden in the white-coloured light! (T15).* Setting up the initial question/problem appeared limited (n=1), and so did the obtaining of conclusions (n=2). Building a model was used in one case by assigning kids to dramatize the motion of the Earth/Moon. Additionally, in three cases, some interaction was implemented, but not related to inquiry, e.g. making a decision about the evolution of the plot, or personal questions.

Discussion

The findings showcase how several narrative functions of fairytales provide opportunities for integrating science instruction. The pre-service teachers extensively used natural phenomena, disasters, or real-world problems to complicate the plot, hence introducing science in an integrated and meaningful way in the story. This supports the literature recommending that non-human 'things' or events can also have agency in science-related stories (Avraamidou & Osborn, 2009). Moreover, fairytales provided space for assisting agents (e.g. a wise owl or a parent) to intervene and provide science instruction in a non-traditional and playful way. Furthermore, findings demonstrate how teachers declined from traditional fairytale patterns by limiting the use of personified villains, wild fights, and romantic themes/marriages, hence educationally appropriating fairytale themes to align with the educational context of preschool children. However, the implementation of stages of inquiry-based teaching appeared limited, and mostly

restricted in expressing ideas. It seems that gathering evidence to make inferences that could affect the plot is demanding; hence, additional guidance and/or scaffolding should be used to transition to more inquiry-based forms of stories. Overall, the findings of this study advocate the affordances of using inquiry-based fairytale-like stories for science teaching.

Pluriversal Emergences: Reading And Living Fractal Possibilities In/Through Afrofuturist Science Fiction

Introduction

We share initial findings from a critical creative inquiry with theoretical, methodological and empirical implications for science education and research. We seek to understand: *how might a collective exploration of Afrofuturist science fiction stories impact our work as a research lab to better support faculty and students in STEMM, in our respective careers, and lives?*

Embracing the era of transition and transformation in science education, The Creativity, Equity and Justice in STEMM (Science, Technology, Engineering, Mathematics, and Medicine/health sciences) research lab, conducts theoretical and pedagogical research, and provides an affinity for Black students at a university in Western Canadian. In Emergent Strategy: Shaping Change, Changing Worlds, brown (2017) describes a mode for working towards just worlds while embracing just practices despite unjust systems for working. Often in academia, what is deemed to be valuable and powerful, such as journal rankings and tenure, does not uphold the values many of us live by, including human dignity and respect (Strong et al., 2016). Aiming to re-imagine existing structures will open up a plurality of space for new, and previously denied ways of being and knowing in STEMM, inclusive of diverse bodyminds (Schalk, 2018) and sociocultural paradigms. brown (2017) laid out six elements to embrace to both unsettle the norms of our workplaces and still thrive professionally and personally: fractal awareness, intentional adaptation, interdependence and decentralization, nonlinear and iterative, resilience and transformative justice, and creating more possibilities.

Theoretical Framework: Afrofuturism And Science Fiction In STEMM

Walidah Imarisha (2015) describes science fiction as "visionary fiction encompass[ing] all of the fantastic, with the arc always bending toward justice" (p. 4). Scholars have theorized how speculative and science fiction, both the reading and creation of, can subvert historical realities and foster revisioning of the normative structures in which we live (Nxumalo & ross, 2019).

Afrofuturism has been uplifted by scholars in STEM education as an innovative, liberatory theoretical approach for Black futurity (Morton et al., 2023). Using “collectivist strategies”, exploratory work with undergraduate Black biology faculty and students, Morton et al. (2023) applied Womack’s (2013) theorization of Afrofuturism, specifically: “1) understanding the multiple truths of the past to ensure a promising, Afrocentric future, 2) an unapologetic centring of and focus on Black culture, Black creativity, Black capabilities, and Black possibilities, and 3) engaging science/speculative fiction, creativity, STEM innovation, and futuristic possibilities within a context that is Black centric” (as cited, p. 9).

Methodology

Engaging through the lens of critical social science theories challenges the conventional norms of who and what is valued in STEMM fields (Strong et al., 2016). Such an approach welcomes imagination for (re)configurations of STEMM and society by infusing radical creativity with critical theory (Bray & Harrington, 2021) to a pluriverse with many co-existing worlds (Leitão, 2022). These methodologies empower participants to identify systems of oppression while collaboratively imagining and constructing new, liberatory frameworks. We shift towards desire-

based frameworks that prioritize community aspirations and collective agency, allowing for transformative possibilities beyond band-aid solutions (Leitão, 2022). Desire is reframed as a destigmatized and generative force, representing the creative impulse and capacity for change. By methodologically framing our critical creative inquiry (Adams, 2018) through our collective desires and desires of Black students, we embrace research activities, like the reading and claiming of science fiction as scholarly work legitimate, and to satiate our desires.

We collectively make methodological decisions around what will become constituted as 'data' in this research, specifically identifying and documenting via fieldnotes and video transcripts of eventful conversations in our meetings which ‘feels like something’ (Stewart, 2020, p. 3). Eventful conversations, as understood here, do not reveal instrumental plans but “rather the possibility of alternative futures, the failures of representations, the contingencies of interventions and the effervescence with which things actually take place” (Vannini, 2015, p. 7). By focusing on data from these eventful conversations, we can learn from reading and discussion to reveal old and new potentialities for collective being, doing and thinking.

Readings with Example Guiding Questions (in sequence)

1. *Introduction in Bodyminds Reimagined: (Dis)ability, Race, and Gender in Black Women's Speculative Fiction* by Sami Schalk (2018)
2. *For I Have Touched the Sky* by Mike Resnick (1989). E.g., How are race, gender, and (dis)ability represented in the story?
3. *The Evening, the Morning and the Night* by Octavia Butler (1991). E.g., How does this reading present medical science, dis/ability, ethics?
4. *Afronauts* written and directed by Nuotama Bodomo (2019).
5. *The Physics of Melanin in The Disordered Cosmos: A Journey into Dark Matter, Spacetime, and Dreams Deferred* by Chanda Prescod-Weinstein (2021).

Findings And Discussion

As brown (2017) was inspired by Octavia Butler, it is unsurprising that we likewise noticed the ways in which Afrofuturist science fiction stories posit nonlinear and iterative strategies. Each week we analysed our experiences of reading to diffract and discern resonant thematic threads across the stories. Themes include:

Leveraging fractal awareness to keep hope alive. Each story sits at the precipice of hope and hopelessness. Ahmed (2013) contends that dominant powers maintain hegemonic relationships via the indoctrination of hopelessness to normalize a sense of changelessness and paralysis of transformative potential. In Resnick’s story, Koriba (the powerful doctor) denies Kamari (a young girl) hope by foretelling the death of a caged bird. Kamari persists to heal the bird in spite of Koriba’s concerns. Solnit (2016) describes hope as an ongoing process of choosing to do something for justice, despite uncertainty. Kamari’s small-scale, hope-filled fractal enactments did not save the bird, yet she still challenged Koriba’s epistemic oppression.

Towards interdependence and decentralization by resisting the young black woman martyr. Central to the stories was a young Black woman martyr (i.e., Matha, Kamari, Lynn). These characters represent resilience, intentional adaptation, moral integrity, curiosity, etc. Take Lynn, who, despite posing harm to herself and others, demonstrated an ironic and powerful resilience when she commits to healing those whose disease causes them to harm. She forfeits a normative independence to embrace a decentralized system that requires interdependence. It goes beyond the utilitarian narrative of for the greater good, as the diseased system she chooses to serve is tabooed. Here lies the creative possibilities for non-linear pluriversal systems (Leitão, 2022).

Forced versus intentional adaptation. Young Black women, in particular, face marginalization

in STEMM (e.g., Strong et al., 2016). In Afronauts, Matha is to be the first person and woman to reach the moon as Zambia enters the space race. As she trains, she becomes an embroiled sacrifice to what an outsider might perceive to be the civilly disobedient intentions of men to colonize space, competing with the colonizer in futility (i.e., the U.S.A, Russia). We see how African nations and peoples, particularly women, are systematically undermined, and how Bodomo uses film to critique how the media stories Black bodies for a colonial audience. Matha's character feels simultaneously coerced and intentional in her sacrifice, suggesting that transformative change can require reconciling things that harm us (in this case, colonization).

By reading Afrofuturist science fiction together we embrace emergent strategies to drive collective and respective professional work in ways that are more human, generative and powerful. We learn from stories' characters how to keep hope alive in the face of injustice (e.g., censoring of equity-language in North America). Through small, fractal moves, we guard against institutionalized hopelessness. Possibilities include heightened attention to daily affirmations both personally and professionally, and group accountability to resist defeatism and despair. Being intentional in our adaptations will mitigate the labour exhaustion, whereby we reject the system working us, and choose to work the system.

Findings will lead to the co-creation of a university course syllabus featuring Afrofuturist speculative fiction through interactive readings and generative dialogues in a salon-style setting. Through a participatory, action-oriented process, learners will be invited not only to make sense of STEMM by describing current issues, but also re-imagine STEMM beyond inequity, seek feedback and iterate, and take action.

With this in mind, we look forward to sharing with researchers and educators how our collective, critical creative inquiry with Afrofuturist science fiction has become a womb of fertile potential and infinite placental transformations, both because of darkness and despite it.

Conclusions

This symposium demonstrates the potential of using storying for science education and provides implications for designing art-based science teacher education settings. Specifically, the aforementioned studies carry out analyses of both existing stories and the stories that participants create in order to explore patterns for a variety of purposes. On the one hand, analysing stories can help researchers examine the integration of content goals, teaching strategies, and epistemological reflections. On the other hand, researchers can gain insights into teachers' emotions and identities, as well as their positionings toward existing social injustices. The findings of the studies showcase the multiple and diverse dynamics of using storying for science teacher preparation and entail implications for curriculum designers in terms of its applicability in several implementation contexts and forms, i.e. both fictional and non-fictional.

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ESERA 2025 Copenhagen

Conceptual Blending In STEM Education: Stimulating Embodiment, Creativity, And Communication

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The purpose of the exploratory seminar was to explore STEM education activities using conceptual blending by combining the aspects related to embodiment, creativity, and communication needed to produce insightful and lasting learning outcomes. According to the theories of embodied cognition and distributed cognition, cognition is not limited to the manipulation of symbols in an individual's brain. Rather, cognition is anchored in our physical environment, through our perception, manipulatives, and socially dependent on shared culture and communication. Regarding conceptual blending, studies point to the general problem of achieving conceptual stability arguing that material structures act as material anchors for blending. Using examples from empirical research studies in engineering, physics, biology and mathematics education, we first discussed how conceptual blending can be used to design embodied educational experiences. We framed the seminar around the question: How can the conceptual blending theoretical framework be used to model and analyse learning in STEM education, focusing on embodiment, creativity, and communication? After introducing the participants to the theoretical aspects related to conceptual blending, they were asked to work in small groups and apply their own experiences of blending, embodiment, creativity, and communication to phenomena of their choosing. Each group presented results of their activity and a whole group discussion was led by the organizers of the exploratory seminar. Following the conference, we would like to invite all participants to further investigate how conceptual blending can be applied in STEM education.

Keywords: Embodied Cognition, Multimodal Learning, STEM Education

Introduction

Against the background of the focus of Strand 6 of the ESERA 2025 conference on theories and models related to inter/multi/trans-disciplinarity in STEM education, we gave an exploratory seminar on conceptual blending as a theoretical framework in exploring the role of embodiment, creativity, and communication in fostering learning in STEM disciplines.

STEM disciplines are particularly suited to fostering the development of technical and creative skills necessary in an increasingly technological and innovative world. To answer the formidable challenges of globalization and the complexity of life it is necessary to educate on complexity and overcome separations between disciplines (Lensing & Pilous, 2022). But how can we foster learning in this context?

Insightful and sustainable learning is characterized in particular by embodied experiences, problem solving, and multimodal communication (e.g., Clement, 1994; Nathan, 2022; Santos-Trigo, 2024). Embodiment maps sensorial experiences (i.e., audial, tactile, visual, etc.) that ground learners' conceptual understandings on to abstractions (Barsalou, 2008). Problem solving is strictly related to creativity in producing novel features and strategies during solution generation. Multimodal communication is related to expressions of conceptual understandings

depicted and described during reasoning and problem-solving tasks (Grondin et al., 2022).

Lakoff (1987) and Johnson (1987) have been part of developing the field of embodied cognition. They contend that our cognition and language are rooted in embodied experiences, which form fundamental conceptual structures known as image schemas. For instance, through physical interaction with our environment, we develop a container image schema, a foundational structure that allows us to conceptualize objects as being inside or outside a bounded space. This schema can be expressed linguistically using metaphors, as in the sentence, "John is in the kitchen". Lakoff and Núñez (2000) have demonstrated that even mathematics – one of the most abstract areas of human thought – is grounded in embodied experiences; for example, the concept of an equation is built upon a shared balancing image schema. Image schemas are grounded in fundamental experiences but may not be (consciously) formed in the moment of creative problem solving. While image schemas provide grounding, creative problem solving often requires reconfiguring and integrating multiple sources of knowledge in context. This means that something other than experience is needed to produce authentic problem solving that implies the emergence of novel features. Indeed, each authentic problem-solving activity requires a certain kind of novel strategy. This leads us to the importance of creativity in problem solving.

Creativity and communication are key competencies of the 21st century (Ananiadou & Claro, 2009; Pellegrino & Hilton, 2012), necessary to face the exponential growth of innovation in all areas of life associated with technological progress and scientific advancement (Leikin & Sriraman, 2022) and are also essential ingredients in reasoning and problem-solving processes (Haavold & Sriraman, 2022; Leikin & Elgrably, 2022; Schoevers et al., 2022).

But what kind of theoretical framework allows the combination of these three perspectives for insightful learning highlighted above: embodied experiences, problem solving, and multimodal communication? Drawing on our joint experiences from a working group on the theme of conceptual blending (1st Specialist Seminar on Embodied Education, Brixen, Italy, 26-28 September, 2024), we suggest conceptual blending as a promising framework for this combination in STEM education.

Conceptual blending theory

Conceptual blending was developed by cognitive linguists Fauconnier and Turner (2002) to understand human cognition. Understanding and learning about the world combines and recombines multiple mental spaces into a single "blended" space. This new space retains some of the input spaces' characteristics but also includes novel emergent properties and features.

According to Hutchins (1995), conceptual blending also provides a useful framework for considering the joint contributions and mutual constraints of mental and material structure. In this approach, framed by the theory of distributed cognition, cognition is not confined to manipulation of symbols in an individual's mind. Rather, cognition is materially anchored in our physical surroundings, through our perception, technological tools, etc., and socially dependent on shared culture and communication. In relation to conceptual blending, Hutchins (2005) points to the general problem of achieving conceptual stability, in terms of knowing what elements and relations can change and which need to remain unaltered, in particular when combining inputs of very disparate nature. Hutchins argues that material structure – including but not restricted to technical artifacts – may contribute to conceptual stability by acting as material anchors for blending. In this sense, a "material anchor" for the blend is an input space from which material structure is projected into a blend (Hutchins, 2005), emphasizing the embodied nature of cognition.

Conceptual Blending In STEM Education

In recent years, conceptual blending has been adopted as a theoretic and analytic approach in STEM education research.

Research examples from physics education describe how conceptual blending can be used to frame embodied aspects of teaching and learning. Dreyfus et al. (2015) analysed how students' simultaneous use of gestures and speech – representing distinct ontological understandings of energy – can be examined through a conceptual blending perspective. Close and Scherr (2015) showed how participants in a role-play scenario use bodily movements, gesture, and language to enact physical scenarios involving energy transformation. Gregorcic and Haglund (2021) employed a conceptual blending analysis of a computer-supported collaborative learning environment that used interactive whiteboards to teach orbital motion of planets and satellites, in which students experienced that they could throw planets into orbit.

In the context of biology education, students have been found to struggle with understanding plant nutrition (Michelsen et al., 2022). Students' everyday experiences in different source domains, such as human nutrition and human respiration may serve as input spaces for understanding the abstract target domain of plant nutrition. This result is surprising because knowledge of photosynthesis is of central importance for solving climate and environmental problems. However, a scientifically compatible understanding of several aspects of the phenomenon, such as the role of carbon dioxide in the air, has been found to require some element of creative thinking (e.g., a new combination of a source and a target domain) (Michelsen & Groß, 2025) and this aspect seems to be closely related to the unique emergent characteristics that are typical for conceptual blending.

As shown by Gelmi, Garzetti, and Asenova (2024), in mathematics education research, different levels of a kind of creativity which is relevant for educational purposes, named "mini-C" by Beghetto and Kaufmann (2007) and defined as the "novel and personally meaningful interpretation of experiences, actions and events" that is "involved in personal knowledge and understanding" (p. 73) can be framed by different kinds of conceptual blending networks, each of them coped with the emergence of some degree of cognitive flexibility or novelty.

In the context of engineering education, Grondin et al. (2022) explored multimodal communication during a reasoning task. Gesture and speech were used to depict and describe the concepts related to torsion. Results indicated that students invoked conceptually discordant gestures (i.e., misalignment between gesture, speech, and concept) indicative of their emerging conceptualizations presumably generated through conceptual blending. Blends produced during reasoning and problem solving that account for communication, they contend, can institute more valid methods for assessing student learning.

In summary, conceptual blending seems to have the potential to be a suitable theoretical and methodological tool to frame, analyse, and assess the distributed, embodied, creative, and communicative aspects of meaningful learning stemming from reasoning and problem solving in different areas of STEM education.

Exploratory Seminar On Conceptual Blending In STEM Education

The purpose of the exploratory seminar was to explore STEM education activities using conceptual blending by combining aspects of embodiment, creativity, and communication that support insightful and lasting learning outcomes.

Specifically, after introducing the participants to the theoretical aspects related to conceptual blending, they were asked to work in small groups and apply their own experiences of blending, embodiment, creativity, and communication to phenomena of their choosing. Each group

presented the results of their activity and a whole group discussion was led by the organizers of the exploratory seminar.

The aim of the seminar was to bring out different perspectives on the integration of embodiment, creativity, and communication through conceptual blending, thereby supporting the theorization of concept integration in STEM education.

The question we discussed with the participants was: How can the conceptual blending theoretical framework be used to model and analyse learning in STEM education, focusing on embodiment, creativity, and communication? Issues concerning the use of metaphors and analogies in relation to embodiment, distributed cognition, creativity, and communication were raised during the seminar and further explored by the authors in post-seminar discussions. In what follows, we outline this exploration and the theoretical insights gained from it.

Metaphors, Analogies, And Conceptual Blending In STEM Education

During the exploratory seminar, and in continued discussion among the authors and some participants, the role of metaphors and analogies in relation to embodiment, creativity, and communication in STEM education was addressed. Two complementary perspectives emerged. One emphasized structural metaphors grounded in analogical reasoning, in which systematic correspondences are established between a familiar source domain and a target domain, as commonly discussed in mathematics and science education (e.g., Pimm, 1981). The other drew on accounts of cognitive metaphors, grounded in embodied experience and image schemas, as developed within embodied cognition approaches (Johnson, 1987; Lakoff & Núñez, 2000).

In line with Fauconnier & Turner (2002), we suggest that rather than treating these perspectives as incompatible, conceptual blending offers a theoretical perspective in which analogies and metaphors may be interpreted as related forms of conceptual integration. From a conceptual blending viewpoint, both analogies and metaphors involve the selective projection of structure from multiple input spaces into a blended space. Structural metaphors based on analogy can be described as blends in which one input space provides a relatively stable relational structure that organizes elements from another space (e.g., single-scope blends). Cognitive metaphors, by contrast, often involve blends in which embodied experience and abstract conceptual structures jointly constrain meaning (e.g., double-scope blends), potentially giving rise to emergent properties that are not fully reducible to direct structural correspondences.

This distinction is relevant for STEM learning, where metaphors and analogies are frequently introduced as instructional resources to support understanding. During reasoning and problem solving, however, learners may elaborate and transform these resources in ways that go beyond their initial instructional framing. From a conceptual blending perspective, such transformations can be understood as processes in which metaphorical and analogical structures are re-integrated with embodied experience, disciplinary knowledge, and representational practices, occasionally supporting novel and personally meaningful interpretations during learning.

Conceptual blending also draws attention to the role of communication and multimodality in metaphor use. Metaphors are not only cognitive constructions but are enacted and negotiated through language, gesture, diagrams, and material or digital artifacts. Multimodal expressions of metaphor can provide insight into learners' evolving conceptualizations, particularly in situations where different modalities are not yet fully coordinated.

Overall, conceptual blending may provide a useful theoretical lens for relating structural metaphors, cognitive metaphors, and analogical reasoning within a single account of embodied, creative, and communicative aspects of learning in STEM education, while leaving room for

domain-specific differences and further empirical examination.

Conclusion

The reflections on conceptual blending, metaphors, and embodiment presented in the previous section help contextualize the contribution of the exploratory seminar within broader theoretical discussions in STEM education. In this sense, the exploratory seminar contributed to ongoing discussions within ESERA Strand 6 by suggesting that conceptual blending may serve as a boundary framework for relating different theoretical models of metaphor, embodiment, and meaning making across STEM disciplines, rather than as a unifying theory that replaces existing perspectives.

After the conference, participants at the exploratory seminar were invited to virtual meetings in the working group on conceptual blending that was formed at the Specialist Seminar on Embodied Education, with the purpose of further exploring how conceptual blending can be applied in STEM education.

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ESERA 2025 Copenhagen

ΘΕΑΝΩ [THEANO] Project: Integrating Drama-Based Pedagogies For STEAM Teacher Preparation

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Interdisciplinary teaching approaches have received increasing attention in the science and STEM education literature. Further ambitious approaches aim to integrate arts-based approaches as a creative, entertaining, and effective way to teach science. This project examines the implementation of drama and story writing in the context of preservice teacher education. This poster presentation presents an overview of the planned structure of the project, along with findings from pre-pilot studies using drama and story writing for designing science teaching. Findings revealed that teachers made good use of story writing to represent science concepts and phenomena through imaginary stories, which entailed imaginary plots, events and characters. However, when called upon to dramatize science teaching material, the plots of most of their dramatizations lacked much action and improbable events. Teachers' reflections high valued the implementation of such approaches since they present science in a more understandable and engaging way. The outputs of the study inform the development of arts-based teacher training programmes in terms of the affordances and challenges that such approaches entail.

Keywords: pre-service teacher education; play and science learning; instructional design

Introduction

Contemporary scientific research has been steered to address real-world problems in order to provide solutions to sustainability issues which are complex and interdisciplinary by nature, such as climate change, nanotechnology, energy crisis, and artificial intelligence. Furthermore, contemporary problems are characterised by uncertainties and complexity (Barelli et al., 2022; Levrini et al., 2021; Miani et al., 2025), which signifies the need to teach the transition to post-modern views of science (Levrini, 2025). Consequently, there appears to be a need to educate students in interdisciplinary teaching approaches (EU Commission, 2015; NRC, 2014) and to prepare them in Future-Oriented Science Education competences (Levrini et al., 2021).

In response to these needs, recent science education literature has highlighted the promotion of integrated Science, Technology, Engineering, and Mathematics (STEM) education. STEM by definition entails the integration of several disciplinary areas (Martín-Páez et al., 2019), which appears challenging given that teachers often come into STEM having different disciplinary backgrounds and expertise which affects their views (Nipyrakis, Stavrou, & Avraamidou, 2024) and practices (Nipyrakis, Stavrou, & Avraamidou, 2024b).

This challenge is exacerbated in STEAM approaches that further aim to include art, since art is stereotypically perceived as radically different from science (Hadzigeorgiou, 2016). However, philosophical views of science tend to regard art and science as 'branches of the same tree' (NASEM, 2018), hence as complementary ways that both acquire and interpret knowledge of the world (Hadzigeorgiou, 2016; Jacobson et al., 2016).

Integrating art can impact not only students' cognitive skills in science, but also affective variables such as interest, engagement, and empathy (Odegaard, 2003). The Arts highlights aspects of science which are often neglected, such as imagination, creativity and emotions, while they also embrace several cultural, linguistic, and multi-literacy assets (Nipyrakis & Varelas, 2025; Varelas et al., 2022). Hence, such an approach allows the participants to express, negotiate and develop their identities in science, especially regarding people from historically marginalised

communities in science (Chappell & Varelas, 2019; Chappell, 2024; Varelas et al., 2024). Moreover, the arts activate multimodal ways of teaching and learning (Varelas et al., 2022; Woodard et al., 2023; Woodard et al., 2024); hence, a more holistic development of the students' personality is taken into consideration through arts-based approaches in science.

Specifically, this project focuses on integrating the art forms of theatre and creative story writing. Regarding stories, in the context of primary and preschool education, they can take the form of imaginary fairytales (Nipyrakis et al., 2025; Nipyrakis, Pantagias & Chalkou, 2026). The act of story writing allows the students to realise, express, and negotiate their understandings as well as their identities, hence providing insightful research data (Varelas, et al., 2012). Furthermore, they can help students build cognitive capabilities for scientific thought by activating curiosity, imagination, and creativity (Fleer, 2019).

As concerns drama, it can take various form, such as the form of a structured science-related play (Pantidos et al., 2001) or an improvised theatrical action, e.g. through 'science improv' (Nipyrakis, 2026). Through theatre, science content can be represented in a more favourable and engaging way for students (Pantidos et al., 2001), while it can contribute to students' understanding the content and methodologies of science (Tselfes & Paroussi, 2009). It also allows students to move further from oral communication and develop their multiple literacies including embodiment, gestures, gaze, sound, music, and engagement with artefacts (Chappell, 2024; Varelas et al., 2022). Therefore, training the new generation of teachers in integrating these two art forms appears promising for science education.

In this direction, this project aims to investigate the integration of the art forms of story writing and dramatizing in a pre-service teacher education programme. Particularly, the study examines how pre-service teachers implement these art forms for designing science instruction, and how they perceive this approach regarding its educational value and implementation. The research questions that guide the implementation of the ΘΕΑΝΩ project are as follows.

RQ1) How do pre-service teachers integrate story writing and dramatizing for teaching science?

RQ2) What are the pre-service teachers' views on integrating story writing and dramatizing for teaching science?

The outputs of this project aim to formulate recommendations for STEAM teacher education designers at the Higher Education level. Particularly, it aims to provide guidelines for effectively integrating the arts-based approaches of story-writing and story-performing for science teaching based on empirical findings which value the needs and the views of the pre-service teachers.

Methodology

This study is theoretically framed within arts-based research (Barone & Eisner, 2012) and the model of Educational Reconstruction for Teacher Education (ERTE, Van Dijk & Kattmann, 2007). Particularly, we chose arts-based research in order to investigate aspects that are often ineffable through the limited constraints of discursive communication (Barone & Eisner, 2012). Hence, an arts-based approach may examine multimodal and artful representations that widen the lens of analysis and may shed light to deeper insights regarding teachers' views and practices in science.

As concerns the subject matter to be taught and learnt in such an approach, according to the ERTE model, it should be educationally reconstructed concerning its educational significance and based on students' conceptions of the phenomena. Furthermore, the learning environments designed by teachers dynamically interact with empirical studies on teachers' pedagogical content knowledge and the design of teacher education environments. In the context of this project, arts-based

methods are used to analyse multimodal data such as the participants' dramatizations, written stories/scripts/scenarios, brainstorming discussions and reflections.

Outline Of The Project

This project is carried out in the context of the first author's postdoctoral research at the academic Departments of Primary and Preschool Education at the University of Crete, Greece. The five main phases of the project are described as follows.

a) Literature review on STEAM integration, arts-based approaches to science teaching, drama-based pedagogies and story writing for science teaching. Particularly, examples from empirical studies and prior implementations are examined in order to help design the pre-service teacher education programme and the arts-based methods. In parallel, science content topics are educationally reconstructed, and STEAM activities are developed to be implemented for the teacher education programme. Specific attention is paid to topics related to sustainability and Future-Oriented Education. Implementing insights and recommendations from pre-pilot implementations of STEAM activities in the design of the STEAM activities.

b) First implementation of STEAM activities in pre-service teacher preparation courses related to science education. Data collection and data analysis from the implementation.

c) Revision and redesign of the STEAM activities based on the findings from examining the first implementation.

d) Second implementation of the STEAM activities in their revised form. Data collection and comparative analysis of data coming from the two implementations.

e) Formulation of recommendations and guidelines for teacher education designers and policymakers regarding arts-based STEAM teacher education programmes.

Currently, the project is in its first phase, where STEAM topics to be used for developing the STEAM activities are examined for their educational significance and are educationally reconstructed. In parallel, we carry out a literature review on STEAM integration that will inform the design of the STEAM activities to be implemented for pre-service teacher preparation.

We also draw insights from the findings from pre-pilot implementations of drama-based pedagogies and story writing activities in order to develop the STEAM teacher education programme. These implementations were carried out before the official start of the postdoctoral project and, hence, inform the design of the pre-service teacher education programme.

Data Collection And Analysis

Data collected from pre-pilot implementations of the STEAM activities include a) the science-related stories composed by the pre-service teachers, b) the video recordings of their dramatizations, c) post-interviews, and d) pre- and post- questionnaire responses of teachers' views and experiences in using drama and creative writing for science instruction. The teachers who participated in the study until now have signed consent forms for participating in the study, while the study has been approved by the Research Ethics and Integrity Committee of the University of Crete.

The analysis of multimodal data such as the dramatizations is carried out through multimodal discourse analysis (Kress & Bezemer, 2023), particularly seeking inductive codes and patterns from teachers' discussions, actions and performance. Textual data, such as the scripts and transcripts of the discussions, are analysed through qualitative content analysis (Mayring et al.,

2015). Particularly, the developed dramatizations and stories are analysed concerning their overall structure and the degree to which they engage science, and in what ways i.e. in which part(s) of the story/performance science was integrated, and whether science was meaningfully integrated into the plot. Further aspects examined relate to the extent to which they implement science teaching methodologies such as stages of inquiry-based teaching (Castillo-Hernández et al., 2021).

The interview and questionnaire data are qualitatively analysed based on the potentialities and challenges that teachers identify, the educational value that they see in such approaches, and the teachers' willingness to implement such approaches in their future teaching practice. Particularly, inductive codes are identified in each theme and are further grouped into emerging patterns relevant to the research questions.

Findings

Preliminary findings from the pre-pilot implementations have tested arts-based activities that integrate drama-based pedagogies and story writing in various forms, such as creative essays to be developed as homework, group activities during the classroom time, warm-up exercises in class as well as post-reflections of such approaches. The warm-up and groupwork activities in class were deemed as necessary since most teachers in their pre-questionnaire responses stated that they had limited or no experience in using these artforms for educational purposes.

As regards the activities related to story-writing, the findings revealed that the preservice teachers developed stories in the genre of imaginary fairytales on a variety of topics. Most topics related to the early childhood science curriculum, such as the water cycle and changes of states of matter, weather phenomena and natural disasters, free fall, etc. This reveals that story-writing in the form of fairytales is dynamically appropriate to relate to early childhood science content.

Moreover, the teachers used a variety of models and metaphors to represent science, either through personifying natural objects as characters of the story (e.g. a droplet, ice-cream, the earth, etc.), or through introducing natural phenomena (e.g. disasters, weather phenomena) to complicate the plot. In most cases (n=17 out of 28 stories), science was meaningfully integrated into the plot, i.e. science was integral to the plot. However, there were cases where the story was focused on science and action in the story was limited (n=2) or absent (n=5), while in 3 stories there was a plot and action, but limited relevance to science, or science was not meaningfully integral part of in the story (n=1).

Concerning dramatizations, the teachers were assigned to develop dramatizations in the form of 'science improv' (Nipyrakis, 2026). The analysis of the preservice teachers' dramatizations revealed that most teachers developed dramatizations without complicated action and having few contingencies. Particularly, most teachers chose to present a science phenomenon by adding a group chat with peers about the phenomenon during the video-recorded performance. Character building and unexpected events appeared limited in the dramatized action. The findings support the use of enhanced guidance or scaffolding when it comes to story performing by themselves, contrasting the findings of imaginary fairytales, where teachers seemed to be more comfortable creating more complex plots.

As regards the teachers' views on using story writing and drama for science instruction, teachers regarded using these art forms as interesting, creative, and effective for understanding science. Teachers expressed a high level of willingness to implement such approaches in their future practice in schools. However, some teachers stated that they felt uncomfortable or shy at the beginning of dramatizations, something that was subsequently overcome. Another challenge mentioned was the prerequisite knowledge in science needed in order to be able to dramatize the

science-related story/action effectively.

Discussion

This study presented an overview of the postdoctoral research ΘΕΑΝΩ (Theano), and it also examined the findings from pre-pilot implementations of STEAM activities that integrate drama and story writing for teaching and learning science. The findings inform the development of subsequent STEAM activities for preservice teacher training in the context of the ΘΕΑΝΩ project. Particularly, the findings highlighted the potentialities that drama and story writing offer for science teaching, including the metaphorical representation of science concepts and phenomena, which, according to teachers, was deemed joyful, creative, and contributes to understanding science. Findings confirm the literature that supports the use of models and metaphors in narratives as an interesting and effective way of understanding science (Halkia & Mantzouridis, 2005; Nipyrakis & Varelas, 2025; Pantidos et al., 2014).

On the other hand, further guidance seems necessary when the teachers dramatize themselves science-related stories in order to develop complex plots. It seemed that teachers using their bodies and selves instead of imaginary characters is far more demanding for developing a complex plot. Massi & Benvenuto (2001) supported that imaginary stories can assist participants to freely express their opinions. The findings of this study support that it might become more difficult or demanding when the teachers embody the story characters. We could hypothesise that this is not only due to initial feelings of shame, but also due to the increasing difficulty of improvising and performing stories. Hence, subsequent iterations of implementing the activities plan to provide more scaffolds and assistance in dramatizing science-related plots through extended engagement and workshops.

For the needs of the conference poster presentation, we showcase the implementation of some representative STEAM activities along with examples of developed stories and dramatizations. Hence, we provoke discussions with the audience members in terms of their educational significance and appropriateness for preservice teacher training and co-reflect on the findings in order to redesign the STEAM activities.

Implications of this project relate to designing innovative arts-based pre-service teacher education programmes for science education, specifically through the use of story writing and theatre. The findings aim to develop guidelines and scaffolds for implementing such practices in the science classrooms.

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Section: Interdisciplinarity As A Curricular, Professional, And Organisational Challenge

ESERA 2025 Copenhagen

Perspectives And Challenges For Interdisciplinary Teaching Practice In Natural Sciences In Brazil

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The teaching of natural sciences plays a fundamental role in contemporary education. Despite scientific and technological advances, new challenges and uncertainties are emerging, such as climate crises, highlighting the need for a more integrated approach to science education. However, the traditional emphasis on specific content unrelated to the student's context has made it difficult for them to understand and act in an increasingly complex and interconnected world. It is essential and urgent to incorporate an interdisciplinary and integrated perspective into teacher training. In this context, the Brazilian National Common Core Curriculum (BNCC) proposes the integration of knowledge in the natural sciences, encouraging a more connected view of natural and technological phenomena. This study seeks to analyse the implementation of the National Common Core Curriculum (BNCC) for the area of Natural Sciences in Brazilian secondary schools. The focus is on teachers' perceptions of the challenges and opportunities brought about by the new curriculum structure, which requires contextualized and interdisciplinary teaching. Using questionnaires applied to Biology, Physics and Chemistry teachers, this study identifies significant difficulties related to infrastructure, curriculum integration and professional training, reflecting on the implications of these issues for educational practice and the quality of science education. For the BNCC to become a transformative tool, it is essential to invest in teacher training, the development of appropriate materials and the adaptation of schools to meet the new pedagogical demands.

Keywords: BNCC; Natural Sciences; Secondary Education; Interdisciplinarity; Teacher Training;

Introduction

We are currently living through a period of intense social transformations that have an impact on the relationships between science, technology, nature and humanity (Levrini et al., 2024). Although scientific and technological advances offer new possibilities, they also generate uncertainties and challenges (Pietrocola et al., 2024). Climate crises, for example, reveal the vulnerability of production systems to the complexity of natural phenomena (Magnasson, 2021; Latour, 2020). In this context, curriculum integration becomes an urgent necessity, requiring collaboration and dialogue between different types of knowledge (Leite, 2024).

Researchers and educators have long warned of a crisis of meaning in the teaching of natural sciences. In the past, science education focused on transmitting content that was far removed from the students' reality, but this approach has become obsolete (Fourez, 2003), especially with the spread of the internet and artificial intelligence, which make access to knowledge broader and more immediate. As a consequence, for nearly two decades, there has been a drop in young people's interest in scientific subjects (Sjøberg, 2002a, 2002b).

Studies indicate that young people seek meaning and relevance in their educational experiences and value spaces where their opinions are taken into account. However, the way the natural sciences and maths are taught in schools, often presented as having absolute truths, makes engagement difficult. This epistemological rigidity contributes to the perception that these subjects are poorly connected to personal and social life (Stuckey et al., 2013), demotivating

students even more than in previous periods (Sjøberg, 2001, p. 21).

In Brazil, the implementation of the BNCC has brought a new dynamic to basic education, establishing guidelines for school curricula to integrate fundamental aspects of students' education. The area of knowledge Nature Sciences lists skills and competences to be developed throughout basic education in the thematic axes: *Matter and Energy*, *Life and Evolution* and *Earth and Universe (Brasil, 2018)*. In this way, content that used to be seen in a fragmented way now needs a more integrated look, so that the conceptual and methodological tools of the curricular components allow students to investigate, analyse and debate problem situations that emerge from different socio-cultural contexts, as well as understand and interpret laws, theories and models, applying them to solve various problems of an individual, social and environmental nature, encouraging interdisciplinary approaches (Leite, 2023) that would allow students to have a more integrated view of natural and technological phenomena.

Previous research has shown that interdisciplinary dialogues in Natural Sciences Education are still limited and unevenly distributed across different configurations of knowledge integration, especially in Brazil (Matsuo et al., 2024). Studies mapping interdisciplinary practices indicate a reduced presence of dialogues even at the micro level, that is, among subareas such as Biology, Physics and Chemistry, and an even smaller number of experiences articulating broader curricular areas (Matsuo et. al., 2024). These findings suggest that interdisciplinary integration in Natural Sciences remains an underexplored field in educational research, characterized by punctual and fragmented initiatives.

However, interdisciplinarity is defended by various actors (Silva and Magalhães, 2016; Morin, 2003; Fazenda, 2017), its practical dimension is quite challenging (Mozena and Ostermann, 2016; Leite, 2023; Matsuo et. al., 2024). As such, the proposal demands significant changes in teacher training and in the organisational structure of schools, which need to be prepared to offer adequate support for curriculum integration. Previous research has emphasised that, in order to implement the BNCC, it is crucial to consider the specificities of education networks and the resources available, as well as supporting teachers' pedagogical adaptation to the new curriculum (Gatti, 2022; Brasil, 2018). This study seeks to explore these issues through the perceptions of teachers in the area of Natural Sciences, who are on the front line of implementation, addressing both the advances highlighted and the practical challenges posed.

Methodology

The research used a qualitative methodology (Bodgan; Biklen, 1994) based on the application of online questionnaires addressed to teachers of natural sciences who work in secondary schools. The sample was made up of teachers from various regions, mostly in the states of Minas Gerais and São Paulo, including municipal, state and public schools, in order to capture a comprehensive view of their experiences. The questionnaire, structured in thematic blocks based on the literature on the subject, covered the participants' professional profile, their experiences in implementing the BNCC and their perceptions of the reform's impact on their work. Data analysis was based on Content Analysis (Bardin, 2016), seeking to categorise the main themes emerging from the responses, such as interdisciplinarity, teacher training, the suitability of teaching materials, among others.

Results

The results show that the implementation of the BNCC in the area of Natural Sciences faces substantial challenges, especially in relation to school infrastructure and teacher training. Many teachers reported that their schools' infrastructure is inadequate to support the practical activities and integrated teaching required by the BNCC. In several institutions, there is a lack of

laboratories, up-to-date teaching materials and even classrooms adapted for interdisciplinary methodologies, which jeopardises the application of the new content in an integrated way. In addition, the lack of teaching materials that dialogue directly with the BNCC proposal was mentioned as an obstacle, forcing teachers to develop their own materials.

Chart 1: Challenges and possibilities of the BNCC in Secondary Education from the perspective of Basic Education teachers.

Categories	Challenges	Positive points
Contents	- Excess or lack of specific content considered important. - Lack of clarity in linking content to the BNCC, making it difficult to apply in the classroom.	- Encouragement to connect content with students' daily lives, making learning more meaningful.
Teacher training and Interdisciplinarity	- Challenges in integrating the disciplines of the natural sciences. - Insufficient initial training for the interdisciplinary approach. - Continuing education needs to be improved in order to train teachers in integrated and interdisciplinary practice.	- Encouraging the use of new methodologies, such as active methodologies and interdisciplinary approaches. - Greater interaction between disciplines, promoting a broader and more integrated view of the natural sciences.
Workload	- Reduced workload for subjects such as Physics and Chemistry. - Difficulty in balancing the depth of content with the time available for the area.	- Curricular flexibility to adapt content and meet students' specific needs.
Teaching materials	- Lack of up-to-date teaching materials compatible with the BNCC. - The need for teachers to develop their own resources, adapting existing materials.	- Reinforcing the importance of teaching materials, favoring a more dynamic learning experience.
Student Motivation	- Challenges in engaging students with a new curriculum proposal. - Difficulty in aligning content with student interests, encouraging active participation.	- Stimulating student protagonism, encouraging active participation and the development of socio-emotional skills.
Curricular flexibility	- Difficulty in adapting pedagogical practices to more flexible teaching. - Challenges in maintaining curricular quality and coherence in the face of change.	- Possibility of personalizing learning, allowing students to choose areas of interest and deepen their studies.

The analysis also highlighted that teachers face difficulties with the concept and practice of interdisciplinarity. Although the BNCC document advocates integrated teaching of Biology, Physics and Chemistry, many teachers feel that their initial training did not prepare them for this approach and that the support offered during implementation was insufficient. Only a minority of those interviewed said they had received some kind of continuing training or institutional support to understand and apply the BNCC's interdisciplinary curriculum. The majority, however, reported having learnt about the new curriculum independently, through their own studies and participation in pedagogical meetings, which were often not enough to resolve all of their doubts.

With regard to pedagogical practice, the teachers pointed out that the rigid structure of the curriculum and the limited workload make it difficult to effectively implement interdisciplinary teaching. Many said that the expectations set by the BNCC in terms of integrating subjects are difficult to achieve in today's school environment, where the pressure to cover syllabus content and prepare students for national exams creates an unfavourable environment for innovative methodologies. The introduction of formative itineraries has been viewed with suspicion by teachers, who perceive a lack of clarity in the organisation of the curriculum and the materials to support this approach. In addition, the majority of teachers reported that students are resistant to the new teaching model, as they are used to more traditional methods.

These findings suggest that while the BNCC offers a potentially transformative vision for teaching natural sciences, its implementation lacks more solid support in terms of training and resources. Teachers believe that successful implementation would require a joint effort between schools and government bodies to ensure adequate infrastructure and develop continuing education programmes focused on interdisciplinarity.

Some Considerations

The study indicates that although the BNCC represents, from the teachers' perspective, an advance in the conception of more integrated and contextualised teaching in the natural sciences, the implementation of the proposal has faced important challenges. The main difficulties identified include the lack of specific teaching materials, insufficient teacher training, both initial and continuing, for interdisciplinary practices, and the reduction in the area's workload, making it difficult to delve deeply into the proposed themes. It is suggested that the success of this initiative depends on a reformulation of initial teacher training, incorporating interdisciplinary perspectives and innovative methodologies. Based on the teachers' perceptions, it can be concluded that for the document to materialise as a tool for transformation, it is essential that education systems invest in extensive teacher training and teaching materials.

The study indicates that although the BNCC represents, from the teachers' perspective, an advance in the conception of more integrated and contextualised teaching in the natural sciences, its implementation has faced important structural and institutional challenges. The main difficulties identified include the lack of specific teaching materials, insufficient teacher training for interdisciplinary practices, and the reduction of instructional time allocated to the area, which limits opportunities for pedagogical deepening and collaborative planning.

These findings suggest that the success of the official curriculum document cannot be attributed solely to individual teachers' efforts or to isolated initiatives in teacher education. Rather, it requires consistent public policies capable of articulating curriculum guidelines, teacher training programmes, working conditions and evaluation systems. Without structural investments in time, infrastructure and institutional support, the expectations placed on interdisciplinary teaching tend to remain at the level of discourse, with limited impact on everyday school practices.

In this sense, interdisciplinarity should be understood not as an immediate perspective choice, but as a long-term process that involves negotiation, experimentation and collective construction among teachers, schools and educational systems. The reduced workload, fragmented schedules and frequent curricular reforms reported by participants compromise the continuity of interdisciplinary projects, restricting them to punctual and fragile initiatives. This scenario helps explain why more complex and sustained forms of integration remain scarce in both school practices and academic research.

From a broader social perspective, strengthening interdisciplinary teaching in Natural Sciences is closely related to the role of education in addressing contemporary challenges, such as environmental crises, technological transformations and social inequalities. Therefore, promoting interdisciplinarity implies rethinking educational policies beyond curriculum documents, including investment in stable professional development networks, collaborative school cultures and long-term planning. Only through coordinated and sustained public action will it be possible to transform interdisciplinary discourse into socially relevant and pedagogically meaningful practices.

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From Fragmentation To Integration: A Case Study Of Interdisciplinary Teacher Education In Natural Sciences

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Teacher education in Natural Sciences has traditionally been organised around disciplinary structures, often reinforcing fragmented approaches to scientific knowledge and teaching. Although interdisciplinarity has been widely advocated in science education research, fewer studies have examined how interdisciplinary principles are concretely conceptualised and operationalised within initial teacher education curricula, particularly in programmes organised by knowledge areas rather than by disciplines. This paper addresses this gap by analysing an area-based initial teacher education programme in Natural Sciences offered by Faculdade SESI-SP de Educação (Brazil). The study adopts a qualitative, theory-informed case study approach based on documentary analysis of the programme's Pedagogical Course Project. The analysis focuses on how interdisciplinarity is embedded in the curricular architecture, the articulation between disciplinary and interdisciplinary knowledge, and the pedagogical strategies designed to support integration throughout the four-year programme. The findings indicate that interdisciplinarity is operationalised through a structured curricular design organised around formative axes that distribute disciplinary depth and interdisciplinary integration across different dimensions of teacher education. Pedagogical strategies such as co-teaching and early engagement in school contexts further support interdisciplinary formation by making visible the relational and negotiated nature of integration. At the same time, the study highlights persistent tensions related to faculty disciplinary backgrounds and the alignment between interdisciplinary teacher education and predominantly discipline-based school curricula. By conceptualising interdisciplinarity as a curricular, pedagogical, and institutional process, this paper contributes to research on science teacher education by offering an analytically grounded account of the possibilities and limits of interdisciplinary approaches in initial teacher education.

Keywords: Science Teacher Education; Interdisciplinarity; Curriculum Integration.

Introduction

Teacher education in Natural Sciences has historically been organised around disciplinary structures, reinforcing fragmented approaches to scientific knowledge and teaching practices. While such organisation has contributed to the development of specialised disciplinary expertise, it has also limited opportunities for future teachers to engage with the complexity of natural phenomena, which often transcend disciplinary boundaries (Morin, 2002; Morin, 2008).

Despite the growing consensus around the importance of interdisciplinarity, research has shown that its implementation in initial teacher education remains challenging. Many programmes endorse interdisciplinary principles at a discursive level, yet struggle to translate them into concrete curricular structures, pedagogical practices, and coherent learning trajectories (Scheie et al., 2025; Klein, 2010). As a result, interdisciplinarity is frequently treated as an aspirational goal rather than as an operational feature of teacher education curricula. This gap between theoretical advocacy and curricular practice highlights the need for studies that examine how interdisciplinary principles are conceptualised and enacted within concrete teacher education contexts.

In the Brazilian context, recent educational reforms and curriculum guidelines have further intensified debates around interdisciplinary teacher education, particularly in programmes organised by knowledge areas rather than by traditional disciplines. Area-based programmes in Natural Sciences aim to articulate Physics, Chemistry, and Biology within integrated curricular

structures, while simultaneously preserving disciplinary depth and epistemic specificity. However, empirical analyses of how such programmes operationalise interdisciplinarity throughout initial teacher education remain scarce in the international literature (Lenoir & Hasni, 2016).

This paper addresses this gap through the analysis of an area-based initial teacher education programme in Natural Sciences offered by Faculdade SESI-SP de Educação, 2024 -Brazil. Rather than presenting the programme as a policy proposal or institutional description, the study examines how interdisciplinarity is conceptualised and curricularised within the programme's pedagogical design. The analysis focuses on the organisation of the curriculum, the articulation between disciplinary and interdisciplinary knowledge, and the pedagogical strategies adopted to support integration across the four-year course.

Guided by these aims, the study seeks to answer the following research question: How is interdisciplinarity conceptualised and operationalised in an area-based initial teacher education programme in Natural Sciences? By addressing this question, the paper contributes to ongoing discussions in science education research regarding the possibilities, tensions, and limits of interdisciplinary approaches in initial teacher education.

Theoretical Framework

The organisation of knowledge into disciplinary structures has historically played a central role in the development of modern science and education. While disciplinary specialisation has enabled significant advances in scientific understanding, it has also contributed to the fragmentation of knowledge, particularly in educational contexts. Fragmentation is not merely a curricular issue, but an epistemological one, as it constrains the comprehension of phenomena whose properties emerge from interactions across multiple levels and domains. From the perspective of complexity, such phenomena cannot be adequately understood through isolated analytical approaches (Morin, 2002; Morin, 2008).

Within this framework, interdisciplinarity emerges as a response to the limitations imposed by fragmented knowledge organisation. Interdisciplinarity is not understood here as the elimination of disciplinary knowledge, but as a relational process that articulates distinct epistemic traditions while preserving their specificities. Rather than dissolving disciplinary boundaries, interdisciplinary work involves coordination, dialogue, and integration among disciplines, allowing for the construction of meanings that cannot be achieved through single-disciplinary perspectives alone (Klein, 2010). This understanding challenges simplified interpretations of interdisciplinarity as fusion or homogenisation, emphasising instead its negotiated and processual character.

In educational settings, interdisciplinarity acquires additional layers of complexity, as it must be operationalised through curricular and pedagogical arrangements. Curriculum integration, in this sense, does not imply the abandonment of disciplinary depth, but its reconfiguration within broader educational purposes. Integrated curricula seek to establish meaningful connections among areas of knowledge while maintaining conceptual rigour and epistemological coherence (Scheie et al., 2025). This perspective is particularly relevant in science education, where the teaching of complex natural phenomena requires the mobilisation of concepts, methods, and explanatory frameworks from multiple scientific disciplines.

Research on interdisciplinarity in school and teacher education contexts highlights both its potential and its challenges. Interdisciplinary approaches have been associated with enhanced relevance, contextualisation, and coherence in learning, yet their implementation often faces institutional constraints, including rigid curricular structures and disciplinary traditions in teacher

education (Lenoir & Hasni, 2016). These challenges are especially pronounced in initial teacher education programmes, where future teachers must simultaneously develop disciplinary expertise and the capacity to integrate knowledge across domains.

Taken together, these perspectives suggest that interdisciplinarity in teacher education cannot be understood solely as a pedagogical choice but must be examined as a curricular and epistemological configuration. They provide the analytical lenses through which the present study examines how interdisciplinarity is conceptualised and operationalised within an area-based initial teacher education programme in Natural Sciences. By grounding the analysis in theories of complexity, curriculum integration, and interdisciplinary knowledge organisation, this framework supports a critical examination of the possibilities and limits of interdisciplinary teacher education.

Methodology

This study adopts a qualitative, theory-informed case study approach, focusing on the analysis of an area-based initial teacher education programme in Natural Sciences. Case studies are particularly suitable for examining complex educational phenomena situated within specific institutional and curricular contexts, allowing for an in-depth analysis of how theoretical principles are translated into concrete educational practices.

The empirical corpus consists of institutional documents related to the Natural Sciences Teacher Education Programme at Faculdade SESI-SP de Educação (2024), with particular emphasis on the Pedagogical Course Project (PPC) implemented for the incoming cohort of 2025. These documents include the official curriculum structure, descriptions of formative axes, and pedagogical guidelines that inform the organisation and implementation of the programme. The PPC was treated not as a normative policy text, but as an analytical object through which curricular and pedagogical assumptions about interdisciplinarity could be examined.

Data analysis was conducted through a qualitative documentary analysis, guided by theoretical perspectives on interdisciplinarity, curriculum integration, and complexity in science education. The analysis focused on identifying how interdisciplinarity is articulated across different dimensions of the programme, considering: (a) the curricular organisation by formative axes; (b) the relationship between disciplinary knowledge (Physics, Chemistry, and Biology) and interdisciplinary curricular components; and (c) pedagogical strategies designed to promote integration, such as co-teaching practices and the Educational Residency Programme.

Rather than evaluating learning outcomes or pre-service teachers' perceptions, the scope of the study is limited to the analysis of curricular and pedagogical structures that support interdisciplinary teacher education. This analytical focus allows for a systematic examination of how interdisciplinarity is embedded in the programme's design, while also acknowledging the limitations of the study regarding empirical data on student experiences. These limitations are addressed in the discussion section, where implications for future research are outlined.

Analysis And Results

The analysis is organised around three analytical dimensions that emerged from the documentary examination of the Pedagogical Course Project (PPC): (a) interdisciplinarity as a structuring curricular principle; (b) the role of formative axes as devices for integrating disciplinary and interdisciplinary knowledge; and (c) pedagogical strategies designed to support curricular integration throughout the programme.

Interdisciplinarity As A Structuring Curricular Principle

Interdisciplinarity in the Natural Sciences Teacher Education Programme is not presented as an auxiliary or complementary element, but as a structuring principle that informs the overall curricular design. Rather than replacing disciplinary knowledge, the programme explicitly seeks to articulate Physics, Chemistry, and Biology through curricular arrangements that promote relational understanding while preserving epistemic specificities.

The PPC conceptualises interdisciplinarity as a process of articulation among disciplines, grounded in the recognition that complex natural phenomena cannot be adequately understood through isolated disciplinary lenses. This conceptualisation aligns with theoretical perspectives that emphasise integration without epistemic dilution, positioning interdisciplinarity as a relational practice rather than as the fusion or homogenisation of disciplinary knowledge.

Importantly, the programme distinguishes between disciplinary depth and interdisciplinary articulation. Disciplinary knowledge is treated as foundational and non-negotiable, particularly in curricular components dedicated to specific scientific domains. Interdisciplinary integration, in turn, is operationalised through curricular structures that create opportunities for dialogue among disciplines, rather than through the elimination of disciplinary boundaries. This distinction directly addresses concerns regarding the potential superficiality of interdisciplinary programmes, highlighting that integration is pursued through coordination and articulation rather than through compression of disciplinary content.

Formative Axes As Devices For Curricular Integration

The organisation of the curriculum around four formative axes constitutes the primary mechanism through which interdisciplinarity is operationalised. Each axis plays a distinct role in balancing disciplinary specificity and interdisciplinary integration, collectively structuring the learning trajectory across the four-year programme.

The axis Specific Knowledge in Natural Sciences is primarily responsible for developing foundational disciplinary knowledge in Physics, Chemistry, and Biology. Within this axis, curricular units are organised to ensure conceptual depth and epistemological coherence within each discipline. Although these units are predominantly disciplinary, their positioning within the broader curriculum allows for subsequent articulation with interdisciplinary components.

In contrast, the axis Interdisciplinary Knowledge in Natural Sciences explicitly targets the integration of disciplinary perspectives. This axis encompasses three complementary orientations: (a) traditionally interdisciplinary fields, such as Environmental Education and Materials Science, where disciplinary boundaries are inherently porous; (b) thematic articulations across Physics, Chemistry, and Biology, designed to overcome fragmentation characteristic of higher education curricula; and (c) reflection on the language, nature, and epistemology of scientific knowledge, framing Natural Sciences as an integrated field of inquiry. Through these orientations, interdisciplinarity becomes a curricular object of study rather than a mere pedagogical aspiration.

The axis Didactics in Natural Sciences operates at the intersection of content and pedagogy, focusing on how scientific knowledge is transformed for teaching. Interdisciplinarity within this axis emerges through the analysis of teaching practices that require the mobilisation of concepts from multiple disciplines, particularly in the context of science education in Basic Education. This axis reinforces the connection between interdisciplinary content knowledge and pedagogical decision-making.

Finally, the axis Education and Teacher Professionalisation situates interdisciplinary formation within broader educational, social, and institutional contexts. Through engagement with educational theory, school practices, and non-formal education experiences, this axis supports

reflective integration across disciplinary and pedagogical domains. The Educational Residency Programme, embedded within this axis, plays a key role in linking curricular integration to real teaching contexts.

Together, the four formative axes create a curricular architecture that distributes interdisciplinary integration across different dimensions of teacher education, rather than concentrating it within isolated curricular units. This distribution addresses concerns regarding the feasibility of integrating scientific and educational knowledge within a four-year programme by structuring interdisciplinarity as a progressive and cumulative process.

This organisation enables interdisciplinarity to function as a longitudinal curricular process, rather than as an episodic instructional feature.

Pedagogical Strategies Supporting Integration: Co-Teaching And Educational Residency

Beyond curricular organisation, the programme adopts specific pedagogical strategies to support interdisciplinary integration, particularly co-teaching practices and the Educational Residency Programme. These strategies function as mediating mechanisms between curricular intentions and pedagogical enactment.

Co-teaching is implemented in selected curricular units, involving instructors from different disciplinary backgrounds. This arrangement is designed to model interdisciplinary dialogue for pre-service teachers, making explicit the negotiation of perspectives, concepts, and methodological approaches across disciplines. Rather than presenting integrated knowledge as a finished product, co-teaching exposes the processes through which interdisciplinary understanding is constructed, including tensions and divergences among disciplinary viewpoints.

The Educational Residency Programme further reinforces integration by situating pre-service teachers in authentic school contexts from the beginning of their training. Residency experiences require students to mobilise disciplinary and interdisciplinary knowledge in response to concrete pedagogical challenges, fostering connections between curricular learning and professional practice. In this sense, residency operates as a contextual anchor for interdisciplinary formation, grounding abstract curricular principles in lived teaching experiences.

While these strategies enhance the visibility and enactment of interdisciplinarity, the analysis also reveals persistent challenges. Co-teaching demands significant coordination among instructors, many of whom were themselves trained in highly disciplinary contexts. Similarly, residency experiences may expose tensions between interdisciplinary training and school curricula that remain largely discipline based. These tensions are not treated as failures of the programme, but as constitutive challenges inherent to interdisciplinary teacher education.

Discussion

The analysis of the Natural Sciences Teacher Education Programme at Faculdade SESI-SP de Educação highlights both the possibilities and the inherent tensions of implementing interdisciplinarity within initial teacher education. Rather than presenting interdisciplinarity as an unproblematic solution to the limitations of disciplinary curricula, the findings suggest that interdisciplinary teacher education is best understood as a structured yet dynamic process, shaped by curricular design, pedagogical strategies, and institutional conditions.

One of the central contributions of this study lies in demonstrating that interdisciplinarity can be operationalised through curricular architecture, rather than being confined to isolated pedagogical initiatives. The organisation of the curriculum into formative axes distributes disciplinary and interdisciplinary learning across different dimensions of teacher education, allowing for the preservation of disciplinary depth while creating systematic opportunities for integration. This

finding resonates with research that emphasises the importance of curriculum-level coherence in supporting interdisciplinary learning, particularly in teacher education programmes that aim to move beyond fragmented approaches.

At the same time, the analysis reveals that interdisciplinarity in this programme is not achieved through the dissolution of disciplinary boundaries, but through their deliberate articulation. Disciplinary knowledge in Physics, Chemistry, and Biology remains a foundational component of the curriculum, especially within the axis dedicated to specific knowledge. Interdisciplinary integration emerges through thematic articulation, epistemological reflection, and pedagogical transformation of content, rather than through curricular compression. This distinction is particularly relevant in addressing concerns frequently raised in the literature regarding the risk of superficiality in interdisciplinary programmes, suggesting that integration and depth need not be mutually exclusive.

The role of pedagogical strategies, such as co-teaching and the Educational Residency Programme, further underscores the complexity of interdisciplinary formation. Co-teaching practices make visible the dialogical and negotiated nature of interdisciplinary work, exposing pre-service teachers to the epistemic and methodological tensions that arise when different disciplinary perspectives intersect. Similarly, early and sustained engagement in school contexts through residency experiences situates interdisciplinary learning within authentic professional challenges. These strategies highlight that interdisciplinarity is not solely a curricular attribute, but also a pedagogical and relational process that unfolds through interactions among educators, students, and institutional contexts.

However, the findings also point to persistent challenges that must be acknowledged. Faculty members' prior disciplinary training may limit their familiarity with interdisciplinary pedagogical approaches, requiring sustained professional development and institutional support. Additionally, the alignment between interdisciplinary teacher education and predominantly discipline-based school curricula remains a source of tension, particularly during residency experiences. These challenges are not unique to the programme analysed but reflect broader structural conditions that shape teacher education systems internationally.

Importantly, this study does not claim to evaluate the effectiveness of the programme in terms of student learning outcomes or professional identity development. The absence of empirical data on pre-service teachers' perceptions and experiences constitutes a limitation of the study but also delineates a clear agenda for future research. Longitudinal studies examining how graduates of area-based programmes navigate disciplinary and interdisciplinary demands in their professional practice would significantly enrich current debates in science education research.

By conceptualising interdisciplinarity as a curricular, pedagogical, and institutional process, this study contributes to the literature on science teacher education by offering an analytically grounded account of how interdisciplinary principles can be embedded within initial teacher education programmes. Rather than positioning interdisciplinarity as a normative ideal, the findings highlight its operational conditions, constraints, and transformative potential, providing insights for researchers, teacher educators, and policymakers engaged in rethinking the organisation of science teacher education in contemporary educational contexts.

Implications For Science Teacher Education

The findings of this study offer several implications for science teacher education, particularly for programmes seeking to move beyond fragmented disciplinary models toward more integrated curricular approaches. By analysing how interdisciplinarity is conceptualised and operationalised within an area-based initial teacher education programme, this paper contributes empirically and

theoretically to ongoing debates on curriculum design, pedagogical strategies, and institutional conditions in science teacher education.

First, the study underscores the importance of treating interdisciplinarity as a curricular principle rather than as an isolated pedagogical innovation. The organisation of the programme into formative axes illustrates how interdisciplinary integration can be distributed across different dimensions of teacher education, enabling a balance between disciplinary depth and integrative learning. For teacher education programmes, this suggests that interdisciplinarity should be embedded in the overall curricular architecture, rather than confined to specific courses or short-term projects.

Second, the analysis highlights the role of pedagogical strategies—such as co-teaching and early engagement in school contexts—in supporting interdisciplinary formation. These strategies make explicit the relational and negotiated nature of interdisciplinary work, helping pre-service teachers to understand integration as an ongoing professional practice rather than as a predefined instructional outcome. For science teacher educators, this finding points to the need for collaborative teaching arrangements and sustained partnerships with schools as key conditions for interdisciplinary teacher education.

Third, the study draws attention to the institutional and professional challenges associated with interdisciplinary programmes. Faculty members' disciplinary backgrounds and the predominance of discipline-based curricula in schools shape the possibilities and limits of interdisciplinary enactment. Recognising these constraints is essential for avoiding idealised conceptions of interdisciplinarity and for designing support structures, such as professional development initiatives and collaborative planning time, that enable educators to engage meaningfully with interdisciplinary approaches.

Finally, this study suggests directions for future research in science teacher education. Empirical investigations that incorporate pre-service teachers' perspectives, longitudinal analyses of graduates' professional trajectories, and comparative studies across different national and institutional contexts would deepen understanding of how interdisciplinary teacher education influences teaching practices and professional identity formation. Such research would complement the curricular analysis presented here and contribute to a more comprehensive understanding of interdisciplinarity in science teacher education.

Taken together, these implications suggest that interdisciplinary teacher education is not a singular pedagogical solution, but a complex and context-dependent process that requires coherent curricular design, pedagogical intentionality, and institutional commitment. By foregrounding these dimensions, this study offers insights that may inform the development and analysis of interdisciplinary teacher education programmes in diverse educational settings.

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Preparing Teachers For Integrative STEM Education In An Era Of Transition And Transformation: An Innovative M.Ed. Program

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The integration of science, technology, engineering, and mathematics (STEM) is critical in preparing students for an increasingly complex, uncertain and interdisciplinary world. Effective interdisciplinary STEM education requires educators capable of bridging disciplinary divides, fostering critical thinking, and implementing innovative teaching practices. This paper presents an innovative M.Ed. program in integrative STEM education, designed to address these challenges. Grounded in interdisciplinary and constructivist principles, the program prioritizes project-based learning (PBL) to promote active knowledge construction, collaboration, and problem-solving. Two courses particularly anchor these within the program, guiding the participants in designing authentic STEM projects and interdisciplinary teaching units that apply PBL principles and methodologies in real-world contexts. Analysis of the students' reflections reveals the program's effectiveness in equipping educators with 21st-century skills. Participants highlighted the challenges, and their professional development associated with identifying problems, developing assessment criteria, and managing iterative processes, as well as demonstrating enhanced self-regulation and productive collaboration. The program produces graduates well prepared to lead interdisciplinary STEM initiatives, and drive innovation within their educational settings. This paper underscores the transformative potential of well-designed professional development programs in STEM education. It provides a model for empowering educators to drive change, ensuring that graduates of the education system are equipped with the interdisciplinary skills required for success in an unpredictable, technology-driven and environmentally unsustainable world. From a future-oriented perspective, this program aims to create a community of educators committed to continuous improvement and cross-disciplinary collaboration, setting a benchmark for global STEM education reform.

Keywords: STEM Curriculum development, STEM Professional Development, Project-based Learning, Integrative STEM education

Introduction: The Need

STEM education, which emerged in the 1990s, integrates science, technology, engineering, and mathematics to prepare students for an evolving, interdisciplinary world. Historically, STEM has been largely associated with science and mathematics, addressing these in an isolated approach and with limited focus on technology and engineering (Dugger, 2010). Literature highlights the importance of integrating all disciplines to develop students' ability to solve real-world problems, consequently, different STEM curricula and initiatives have been developed to address these gaps (Bybee, 2013; Cagle et al., 2018; Yurchenko et al. 2022).

The need for effective STEM education is increasingly acknowledged as schools are required to equip students with essential 21st century skills. These include teamwork, problem-solving, critical thinking, and the ability to innovate and adapt in a rapidly changing world (Bybee, 2013; Doppelt & Barak, 2021). Unfortunately, many teachers lack the training necessary to integrate STEM disciplines effectively, as they often specialize in a single subject area and lack experience in cross- and interdisciplinary collaboration (Joyce & Dzoga, 2013). In response, the Israeli Council for Higher Education approved the development of an integrative STEM master's program to address these challenges (Dagan et al., 2019). This paper presents principles of this innovative academic program and its impact on the participants.

Ultimately, STEM education aims to prepare students for an unpredictable future. Effective STEM curricula can enhance higher-order cognitive skills and promote deep understanding through collaborative hands-on learning (Bybee, 2013). This will also prepare graduates of education systems with strong motivation and curiosity, ensuring they are well-equipped for higher education and careers in STEM fields.

The Program's Design Principles And Structure

The M.Ed. program 'Integrative STEM Education' equips educators with the skills to lead change in formal and informal educational settings. Drawing from literature, educational policy, and expert consultations, the program focuses on integrating STEM disciplines. It emphasizes interdisciplinary understanding, pedagogical content knowledge (PCK), and leadership, enabling educators to tackle real-world challenges and foster cross-disciplinary collaboration. The program aims to create educators with an interdisciplinary mindset, capable of bridging the unique and shared aspects of STEM fields who can facilitate their students in transferring knowledge and problem-solving approaches across disciplines. Active learning, teamwork, problem-solving, and research methodologies are central. These are achieved through the following objectives:

1. Enhancing understanding of STEM subjects in interdisciplinary contexts supporting the development of critical thinking skills.
2. Developing PCK and TPACK for effective teaching, emphasizing Project-Based Learning (PBL) and active learning environments.
3. Building leadership skills for initiating and leading STEM projects in educational frameworks.
4. Promoting the "teacher as researcher" approach through action research in STEM education.

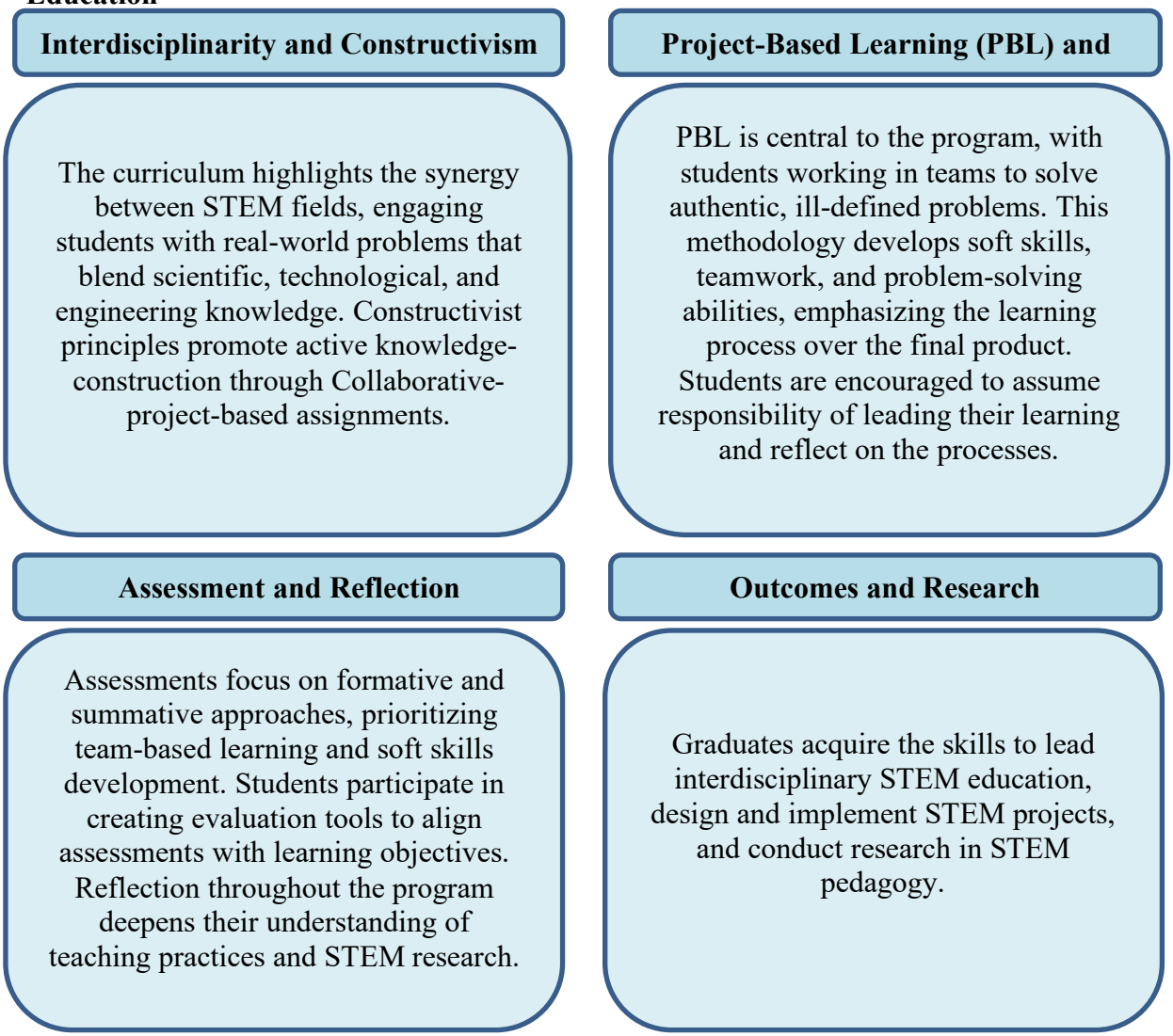
The pedagogical principles and practices of the program are detailed in Figure 1.

The two-year M.Ed. program translates its design principles into a cohesive structure reflecting a progressive developmental process (Figure 2). Infrastructure courses provide the foundational interdisciplinary knowledge and skills that will be employed in the advanced project-oriented courses. Interdisciplinary science-oriented courses such as *Biomimicry* and *Biosphere Research*, together with education-oriented courses like *Education for Values in Science and Technology* and *Computational Thinking*, are key components of the program. The seminars focus on *Reforms in Scientific and Technological Education* and *Action Research on STEM Project Implementation* (Dagan et al., 2023). Two core project-based courses, the focus of this paper, specifically reflect PBL: *Developing an Integrative STEM Project*; *Developing and Implementing an Integrative PBL-based STEM Educational Project*.

From Design To Practice

To demonstrate how the program's design "comes to life", we showcase how its objectives and key pedagogical principles and practices are embodied in the two main project courses. We then highlight student outcomes in these courses and share their reflections on the overall learning experience in this program. As shown in Figure 1. These courses are based on previous infrastructure courses that build a deep understanding of the essence of the interdisciplinary STEM approach, how PBL provides a model for profound problem-solving, and leverage key skills to enhance the interdisciplinary project-based approach. In both courses, students work in multidisciplinary teams in which each member specializes in a different STEM discipline. Beyond peer learning, the aim is to build on the different perspectives towards developing an integrative project. The courses are delivered via co-teaching, implementing the pedagogy of facilitator - serving as guides and advisors through the process.

Figure 1: Pedagogical principles and practices of the M.Ed. program 'Integrative STEM Education'



Development Of STEM Project Via PBL Approach

In this course, students identify an authentic problem with societal relevance and address it employing the PBL framework, with emphasis on the engineering design process. The course culminates in a solution-oriented product and comprehensive documentation of the entire process. This course aims to provide students with hands-on experience in developing a STEM project, engaging in a comprehensive, long-term process (two semesters), which includes navigating challenges, managing frustrations, and celebrating successes. Experiencing this challenging and significant journey first-hand is essential for equipping the students with the competencies to implement such a learning process in their educational contexts. For further details, see Dagan et al. (2023).

Examples of students' products:

- *Umbrecoola*

  The problem: In an era of climate change, how can the body be cooled when outside in increasingly warming environments?

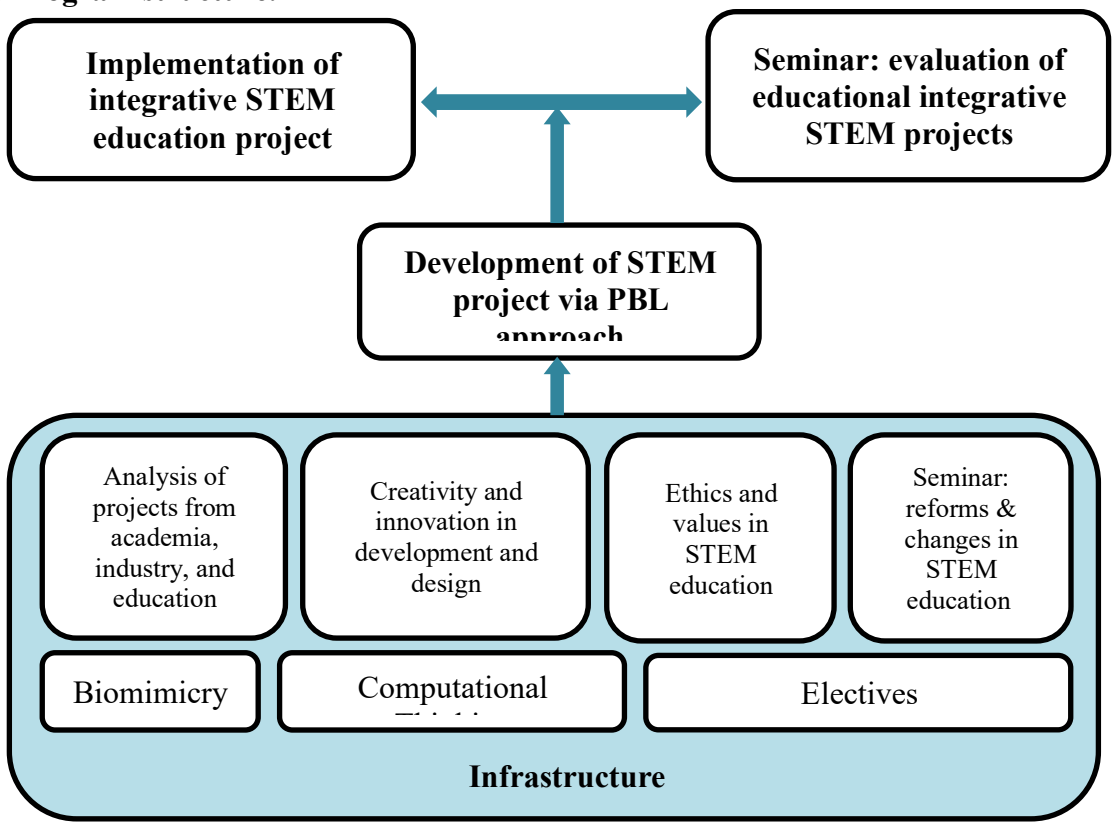
  The solution: A cooling umbrella ("Umbrecoola"). Under the umbrellcoola's canopy, a rechargeable water-based cooler is installed, providing a combination of shading and efficient personal cooling when outside.

- *Walking-Phone*

The problem: How can we assist elderly people who use walking canes in using a mobile phone while walking?

The solution: An adjustable connector attached to the walking cane, allowing a mobile phone to be securely mounted.

Figure 2: Program structure.



Development And Implementation Of An Integrative PBL-Based STEM Educational Project

In this course, students develop a teaching unit that applies interdisciplinary STEM learning through the PBL process and implement it in their educational settings. The implementation is evaluated in an accompanying action research seminar (not detailed here). This course builds on the concepts developed during the previous project. The learning-unit design process begins with selecting a driving question that is meaningful and addresses value-related challenges in the students' educational settings and defining the unit's learning goals. The learning unit incorporates inquiry-based and scientific practices, emphasizes creating a tangible, measurable artifact, and includes formative assessment and reflection. Importantly, the students engage in learning through the PBL process, the learning-unit they design must embody PBL principles, ensuring that their pupils learn through PBL methodologies. For further details, see Ragonis et al. (2024).

Examples of learning units:

- *Ethical gambling – is there such a thing?*

  Driving questions: How are gambling machines programmed in terms of players' luck? What is considered fair gambling? Can fairness be calculated mathematically – How?

- *What did I inherit (genetically) from my parents*?

  Driving questions: Is it okay to select/determine my children's traits? What [inheritable] traits will our children inherit from my partner? What is the probability regarding each trait.

- *Renovating the local safari*

  Driving questions: As the designer of this renovation, what are the central considerations, challenges and solutions in designing an optimal habitat for a selected animal in the safari?

Students' Reflections

Students reflected on their experiences and learning process using a structured protocol addressing seven PBL characteristics (Dagan, 2023). Content analysis of their responses revealed that active engagement in PBL helped them identify its key characteristics and understand their significance for learning. The students faced several challenges inherent in the PBL process, which they addressed and overcame through various strategies. Students acknowledged valuable insights gained about teaching and learning in STEM PBL environments and expressed intentions to apply this in their educational fields:

Identifying the Problem. Defining a motivating yet feasible, multi-disciplinary problem suited to their knowledge, capabilities, and timeframe was challenging. The students viewed STEM knowledge gaps they encountered as opportunities for learning, collaborating with teammates, faculty, and external experts.

Assessment. Developing their own assessment criteria was challenging. However, students recognized its importance for understanding the design process and the skills required for each project component, as it required them to delve into the components' significance to the learning process.

Timetable. Managing the project's schedule proved difficult due to the iterative nature of PBL, often creating frustration. Nevertheless, students appreciated the importance of planning while acknowledging the need for flexibility, as changes are inherent to PBL.

Students reflected that they overcome these challenges by leveraging teamwork, self-regulation, narrowing problem scope, and seeking professional guidance. These strategies reflect essential 21st-century skills, which they aim to instill in their own students. Through this process, students demonstrated their growth and readiness to implement STEM PBL principles in their classrooms, underscoring the program's success in fostering professional and pedagogical development.

Some supportive quotes from students' reflective reports:

> It allows me as a teacher to know where the points of failure are, to know what should be more or less structured, how to assist learners in the process, and above all, how to really implement a PBL project in the best way for all partners in the process." (ES)
>
> "To understand that the main goal of the PBL process is to develop personal abilities along with empathy, which will increase the chances that he/she will grow up to be a person engaged in improving the world." (YN)
>
> "Encountering real-life projects deepened the understanding that to be ready for the future world, students need to learn in an integrative way, to establish broad knowledge in many areas, to understand the connections among these areas and know how to make new connections that will lead to new original developments. (TS)

These students' responses support the idea that in the process of developing the STEM projects, this M.Ed. program, and particularly the above-described PBL-based courses, met the core objectives.

Conclusion - A Future-Oriented Vision

Our vision is to see our graduates applying the approaches and strategies they have learned

throughout the program in their own classrooms. We aim for them to be change-agents within their educational settings, driving progress and innovation. This vision extends to transforming the perception of schools, where the integration of STEM education and project-based learning is seen complementary to existing curricula, rather than conflicting. Ultimately, we hope this program will attract diverse students, creating a sustainable impact on education by fostering a community of educators committed to continuous improvement and cross-disciplinary collaboration, necessary in a constantly changing world.

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Nature Of Engineering For School Science: Insights From Experts

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In today's rapidly evolving world, early engineering literacy is essential for navigating digital and environmental transitions. Science education must adapt to foster interdisciplinary understanding, problem-solving, and ethical reasoning. A comprehensive, unified perspective of the nature of engineering (NOE) is essential for guiding these efforts and fostering informed and engaged citizenship. However, the conceptualization of NOE is complex, and there is no consensus on what should be included in school curricula. Hence, the study aimed to examine experts' views on the aspects of engineering that should be explicitly taught in school science. The study utilized the thematic analysis approach to analyse data collected via semi-structured interviews among engineering education experts. The findings revealed three themes in experts' views: engineering practices, engineering-society concepts, and engineering core ideas. The themes highlight 'what engineers do', 'how engineers think', and 'what engineers know' while addressing societal needs. Each identified theme corresponds with one of the three dimensions of the Next Generation Science Standards (NGSS), as well as with cognitive-epistemic and social-institutional Family Resemblance Approach (FRA) categories. The study underlines the need to identify and classify sets of engineering-specific core ideas that could establish a foundational vocabulary. Addressing this gap could enhance FRA-informed NOE and engineering literacy as part of the school science curriculum. In turn, this would help equip students with the knowledge and skills needed to navigate the societal transformations of our era.

Keywords: STEM Education, STEM Curriculum, Science Education

Introduction

For more than two decades, educators and policymakers have called for promoting engineering literacy from an early stage. This approach aims to deepen the understanding of scientific principles by applying engineering concepts in authentic contexts, thereby fostering an interdisciplinary grasp of the technology-driven world (Antink-Meyer & Brown, 2019; Cunningham et al., 2020). The growing interdisciplinarity of scientific fields stresses the importance of this integration of engineering concepts into the science curriculum (Antink-Meyer & Arias, 2022; Barak et al., 2024; NASEM, 2020; NGSS Lead States, 2013), equipping students for the challenges of the 21st century. But what ideas about engineering should be taught in schools?

There is general agreement that, in order to foster socially aware, innovative, active citizens who are ready to contribute to an equitable, inclusive, and sustainable future, students need to know something about the nature of engineering (NOE). As stated by NGSS, strengthening the engineering aspects will clarify for students the relevance of STEM to everyday life. Specifically, with the growing dominance of STEM in our day-to-day lives, understanding the NOE and its social implications becomes increasingly important. This understanding may foster informed citizenship, equipping individuals to address the challenges of an evolving technological society. In fact, contemporary pluralistic democratic societies strive to cultivate citizens capable of actively participating in meaningful decision-making. To that end, teaching the NOE from an early age is crucial.

However, the conceptualization of NOE is complex, and there is no consensus on the content or the view that should be included in school science curricula to address this complexity (Barak et al., 2024; Pleasants & Olson, 2019; Parrish et al., 2024; Deniz et al., 2020). This is further complicated by the fact that engineering is a multifaceted field that necessitates advanced scientific knowledge and high-level mathematical skills and, therefore, presents notable challenges for both teachers and students (Barak & Usher, 2022; Pleasants & Olson, 2019). Literature on engineering literacy has attempted to create a list of concepts and aspects that should be taught as an integral part of the science curriculum by elucidating learners' NOE understanding (Karataş et al., 2015), conducting Delphi studies (Hartman & Bell, 2017), building upon NOS literature (Deniz et al., 2020; Barak et al., 2024), synthesizing engineering studies from various perspectives (Pleasants & Olson, 2019), and by surveying state standards (Carr et al., 2012). However, there is no agreed-upon set of key aspects that define the NOE.

Teaching engineering concepts in a way that provides students with a comprehensive understanding of their nature necessitates an interdisciplinary, holistic view. This approach involves making connections across domains to foster a nuanced understanding of the engineering practice, along with its complexities and interconnections. NOS researchers have shown that it is naïve to expect students to understand science's nature implicitly simply by engaging in scientific practice (Abd-el-Khalik & Lederman, 2000). It is rather a considerable collective and reflective endeavour, like the images of science that historians, philosophers, and sociologists of science have been constructing. The Family Resemblance Approach (FRA) has been recently borrowed from NOS studies (Erduran et al., 2019) and utilized for framing the NOE as a two-dimensional system. Emerging research suggests that the FRA offers a promising framework to cultivate an inclusive understanding of both the cognitive-epistemic and social-institutional dimensions of NOE (Barak et al., 2024).

Hence, the study's goal was to examine experts' views on the aspects that should be explicitly taught in school science.

Method

The study participants included seventeen leading and acknowledged experts in engineering education, including engineering professors, science and engineering curriculum designers, teachers with an engineering background, and practicing engineers with teaching experience. They were recruited through a purposeful sampling process (Creswell, 2018), starting with distinguished engineering professors, who then recommended other qualified experts from their network. They were specifically targeted to provide educational and pedagogical points of view for the essential aspects that should be taught about engineering in pre-college education. Data from experts were collected through semi-structured interviews with questions pertaining to the conceptualization of NOE. For example: *in your opinion and from your experience, what is important for the average 21st-century citizen to understand about engineering? What are the important aspects of engineering?*

The responses of the engineering education experts were analysed by two educational researchers according to the thematic analysis approach (Braun & Clarke, 2021; Creswell, 2018). The analysis included the following steps: the participants' answers were compiled into a distinct, coherent document; the document was rigorously read, and relevant text segments on what a 21st-century citizen should understand about engineering were marked. The analysis applied an inductive orientation to the data, and coding and theme development were driven by the data content (Braun & Clarke, 2021).

Findings

Experts pointed to the importance of fostering engineering literacy through the development of a nuanced perspective that goes beyond technical problem-solving. They emphasized deliberately engaging students in discussions focused on three themes: engineering practices, engineering-society concepts, and engineering core ideas. The first theme, **engineering practices**, referred to 'what engineers do' to design and build systems, solve interdisciplinary problems, and address real-world challenges. Experts focused on the process of defining human-related problems, developing and using engineering models, and designing solutions. These practices require key competencies, including social behaviors "*such as the ability to work in a team and brainstorm ideas*" (A.A., engineering curriculum designer); or "i*nterdisciplinary communication and collaboration are key… as engineers work, for example, with policymakers to design public infrastructure*" (A.B., engineering professor and curriculum designer). They also referred to cognitive behaviors, including "*one needs to be a lifelong learner and think creatively*" (A.A., engineering curriculum designer) in order "*to use systems thinking to define and solve problems*" (H.F., engineering curriculum designer). Additionally, they pointed out cognitive practices such as "*students need to understand complex trade-offs in engineering decisions*" (R.L., engineering curriculum designer). "*Trade-offs and constraints, like budget and environmental impact, should be introduced as part of the design process*" (M.W., science teacher with an engineering background).

The second theme, **engineering-society** concepts, referred to 'how engineers think', considering ethical, social, and global perspectives while addressing challenges and developing solutions. Experts provided insights into the interplay between engineering and societal contexts and focused on the dynamic, interrelated relationship between engineering and the social, cultural, economic, political, and environmental systems. Experts stressed that:

"When designing an engineering solution, the engineer must consider value-related factors, such as whether the development and the resulting improvement in quality of life align with sustainable development goals, like those established by the UN" (D.B., engineering curriculum designer).

Building on this idea, participants highlighted seeking reliable outcomes, mentioning that:

"Engineers must create environmentally sustainable solutions while also addressing any potential ethical concerns. They need to perform a life cycle assessment and look beyond the solution itself… For example, an electric car – what are the environmental implications of this development? Or transportation as a system - where do you position the bus or train within physical space, and how does this placement impact human behavior?" (A.B., engineering professor).

It was noted that responsibilities regarding the safety of users, equity, and long-term impacts are an important aspect of engineering: *"Engineering solutions impact various aspects of life, like how transportation systems affect urban development"* (A.B., engineering professor); or *"digital technologies and their societal implications on labor markets and daily life"* (D.M., engineering education professor), and "*bias and privacy concerns in AI technologies*" (I.L., engineering education professor).

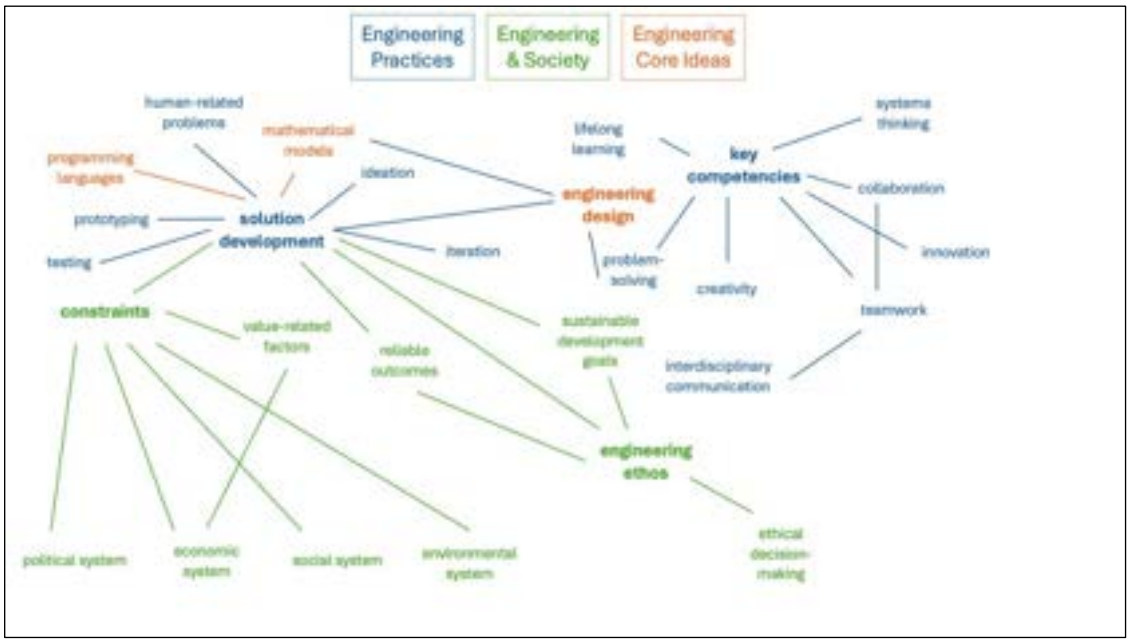
The third theme, **engineering core ideas**, received comparatively less emphasis from experts. This theme encompasses 'what engineers know' - foundational knowledge and disciplinary concepts critical to understanding and applying engineering principles. A recurring theme in the responses was that "*the focus needs to be on programming languages*" (A.A., engineering curriculum designer), "*Scratch programming, for example, is an easy way to teach complex ideas*" (D.C., engineering education professor). Experts also underscored the importance of science and mathematics knowledge as the foundations for understanding engineering:

"…to calibrate a sensor, mathematics is essential. It involves taking two measurements under extreme conditions, deriving a linear equation, and applying a conversion function to translate the signal output into the corresponding physical value being measured" (D.C., engineering education professor).

"For engineering, one must have a solid scientific knowledge foundation, including chemistry, organic chemistry… heat transfer, energy and matter flows, materials, and the principles of acids and bases. Generally speaking, physics, chemistry, and biology are the foundations of mechanical engineering, while mathematics is the backbone for fields such as information systems, data science, and biotechnology engineering" (H.F., engineering curriculum designer).

Figure 1 shows a conceptual map of the various engineering aspects that the participants suggest teaching in schools as part of the science curriculum. It presents the three emerging themes and the links between the concepts, with the top-rated elements highlighted.

Figure 1. Conceptual map of participants' ideas and identified links.



Discussion And Conclusion

This study delves into the engineering dimension of STEM education by bringing the expert community's views on the NOE aspects that should be explicitly taught in school science. Based on the findings, the study suggests conceptualizing NOE as an FRA-informed engineering-specific framework. The FRA's focus on characterization rather than definition of disciplines positions it as a powerful model for balancing disciplinary identities and interdisciplinarity (Satanassi et al., 2023). Each emerging theme corresponds with one of the three dimensions of the NGSS model (NGSS Lead States, 2013), as well as with cognitive-epistemic and social-institutional FRA categories (Barak et al., 2024). The suggested conceptual framework integrates engineering practices, engineering-society crosscutting concepts, and engineering core ideas, similar to NGSS 3-dimensional learning. The responses highlight what engineers do to design and build systems (engineering practices and the FRA cognitive-epistemic dimension), and the connections across fields that drive innovation and address societal needs (engineering-society crosscutting concepts, and the FRA social-institutional dimension).

However, unique foundational ideas that span multiple engineering disciplines (engineering core ideas, or the engineering knowledge FRA category from the cognitive-epistemic dimension) have limited presence in experts' conceptualizations. The model of science learning outlined by NGSS includes the Engineering, Technology, and Applications of Science (ETS) domain as one of its

four DCI domains. This domain consists of two subcategories: ETS1 - engineering design - which emphasizes defining problems, developing solutions, and optimizing designs; and ETS2 – links among engineering, technology, science, and society – which emphasizes the interdependence of these fields and their impact on society and the environment. However, this framework emphasizes science core ideas (like matter and its interactions in physical sciences, or ecosystems in life sciences) and their applications in engineering, without mentioning core ideas that are distinct to engineering. This prompts a deeper examination and possibly an additional subcategory of the core ideas that should form the foundational vocabulary of engineering literacy, ensuring that 21st-century citizens are equipped to navigate technological and societal challenges.

Future research would benefit from strengthening the not-yet-agreed-upon set of core ideas in engineering by defining key ideas central to the field. These ideas may be represented as engineering knowledge under the cognitive-epistemic FRA dimension, relating to scientific and mathematical theories, laws, and models. These core ideas should be broadly applicable across multiple engineering fields, serve as essential tools for problem-solving, resonate with students' interests, address significant societal concerns, and be designed for incremental teaching and learning over time (NGSS Lead States, 2013). These may include systemic core ideas, for example, sustainability is central to structural engineering in the planning and construction of energy-efficient buildings; similarly, safety and reliability play a crucial role in materials engineering in the development and testing of materials for aerospace applications. Alternatively, these ideas may include fundamental core ideas, for example, elasticity is central in materials engineering in analysing and predicting the behavior of materials under mechanical forces; likewise, Reynolds Number is foundational in predicting flow behavior for designing pumps and turbines in machinery engineering or bridges and water distribution systems in structural engineering.

The study's theoretical contribution is in identifying key NOE aspects to be incorporated into school curricula, expanding both the NGSS 3-dimensional model and the FRA. This warrants careful consideration, particularly when balancing competing priorities, navigating complexity, gaining stakeholder support, and addressing practical constraints in curriculum design. The next step is to deepen science teachers' understanding of NOE concepts and provide them with effective heuristics for teaching these ideas.

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Shaping STEM Educators: The Evolution Of Student Teachers' Perceived Importance And Self-efficacy In Integrated STEM

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In recent years, integrated STEM (iSTEM) education has received increasing attention, with research exploring a wide range of factors that influence its effectiveness. Literature seems to incline toward five central principles for high-quality integrated STEM education: "integration", "real-world problem context", "design", "inquiry" and "teamwork". The question why a great variability in effects of integrated STEM education exists, can partly be explained by a variety of instructional practices employed by teachers. Moreover, it has been shown that teachers' attitudes are strongly related to these instructional practices. Despite their importance, little is known about the effect of teacher training in iSTEM on (student-)teachers' attitudes. Therefore, this work-in-progress research longitudinally investigates the evolution of student-teachers' attitudes during their teacher training. Using a slightly adapted validated questionnaire, a cognitive dimension (perceived relevance) and a perceived control dimension (self-efficacy) were distinguished in a survey. Initial descriptive statistical analyses show a V-like trend in the importance student-teachers attribute to the iSTEM principles before, during and after an integrated STEM teaching course. This indicates that students devalue the five iSTEM principles during the course, in contrast to the initial situation, but regain importance by its end. On the other hand, student-teacher self-efficacy rises consistently during the course, especially during the first part. Although further qualitative and quantitative data are needed to confirm and explain these findings, this first-of-its-kind study about the longitudinal changes in (student-) teachers' attitudes towards iSTEM, already provides valuable results for teacher education in integrated STEM.

Keywords: iSTEM education, teacher training, attitudes

Introduction

Integrated STEM (iSTEM) education, which aims to educate STEM specialists and STEM-literate citizens by fostering transitions across STEM subjects, has grown significantly in recent years. Despite diverse perspectives on iSTEM education (e.g. Fan et al., 2021; Kelley & Knowles, 2016; Roehrig et al., 2021), literature seems to converge on five central principles for high-quality integrated STEM education: "integration", "real-world problem context", "design", "inquiry" and "teamwork" (Portillo-Blanco et al., 2024; Thibaut, Ceuppens, et al., 2018).

The objectives of iSTEM education are diverse. Gao et al. (2020) provide a matrix that categorizes intended learning objectives along two dimensions. The first dimension distinguishes objectives related to individual disciplines (monodisciplinary, e.g., calculating a derivative), connections between disciplines (interdisciplinary transitions between STEM-subjects, e.g., using an integral to calculate work), and those that transcend disciplinary boundaries (transdisciplinary transitions between STEM concepts and the real-world or transversal skills, e.g., fostering creativity). The second dimension considers objectives in terms of knowledge, skills, practice (e.g., engaging in scientific investigation), and the affective domain. Numerous studies have illustrated positive effects of integrated STEM approaches on one or more of these objectives (Ali Al-Mutawah et al., 2021; Chang et al., 2022; De Loof et al., 2023; De Loof, Boeve-de Pauw, et al., 2022; De Loof, Boeve-De Pauw, et al., 2022; Le et al., 2023; Mustafa et al., 2016). However, studies also reported neutral or negative effects (Becker & Park, 2011; De

Loof, Boeve-de Pauw, et al., 2022; Le et al., 2023).

The observed variability in outcomes may partly be related to the diversity of targeted objectives and the relative emphasis they receive during teaching, but it is also likely influenced by a diversity of instructional practices used in the classroom. Implemented iSTEM instructional practices significantly affect students' ability to apply knowledge (Thibaut, 2018). Moreover, teachers' attitudes influence the implementation of new educational approaches (Pintó 2005; Roehrig, Kruse, and Kern 2007). For iSTEM, teachers' attitudes are significantly related to their instructional practices (Shahali & Halim, 2024), including the five principles mentioned above (Thibaut, Knipprath, et al., 2018b).

These results imply that teacher training, aimed at fostering positive attitudes towards the iSTEM principles, is crucial for achieving the desired effects. However, in- and pre-service teachers often lack prior experience with iSTEM principles as secondary school pupils, yet they are expected to implement them. Teacher training initiatives therefore face the challenge of familiarizing (student-)teachers with iSTEM while preparing them for actual classroom practice. Given the important impact of teachers' attitudes on their instructional practices, teacher training initiatives should evaluate their effects on (student-)teachers' attitudes.

While previous studies have cross-sectionally investigated the relations between school context, personal factors and/or teachers' knowledge to teachers' attitudes towards iSTEM (Shidiq & Faikhamta, 2020; Sokha, 2024; Thibaut, Knipprath, et al., 2018a), to our knowledge, longitudinal research studying the evolution of (student-) teachers' attitudes during training is lacking. This work-in-progress study therefore aims to address the research question "How do student teachers' attitudes towards iSTEM change during their teacher training program?".

Methods

Participants And Teacher Training Program

This research involved students enrolled in KU Leuven's Master of Teaching in Sciences and Technology. During this teacher training, students, often already holding a disciplinary Master's degree, take pedagogical courses, subject-specific teaching courses and corresponding internship(s), and an integrated STEM course and internship 'Interdisciplinary Education: iSTEM and Natural Sciences'. Depending on their prior Bachelor or Master, students can specialise in the school subjects Biology, Chemistry, Computer Science, Earth Sciences, Engineering & Technology, Physics, and Mathematics. Given the importance of cross-disciplinary linking for conceptual understanding, the integrated STEM course is obligatory for all student teachers. The course (6 ECTS) consists of two parts: (1) iSTEM didactics, where students learn about the iSTEM principles and design their own iSTEM project collaboratively in a multidisciplinary team, and (2) an internship, where student teachers implement the designed project with upper secondary school pupils.

Measures

In line with previous research, we defined "attitude" as the overall evaluation of an object on several dimensions (Ajzen, 2005; Maio and Haddock, 2009; Thibaut et al., 2018a). A conceptual framework for teachers' attitudes towards science was proposed by van Aalderen-Smeets and van der Molen (2015) and build upon for iSTEM by Thibaut et al. (2019). Thibaut's questionnaire included a cognitive dimension (perceived relevance), an affective dimension (anxiety) and a perceived control dimension (self-efficacy). This questionnaire served as the basis for our study, but was slightly adjusted to better reflect the meaning of each iSTEM principle for student-teachers, e.g. the item "How important do you think it is that students find an answer to their own questions?" was split up in "... that students formulate their own research questions?" and "... that

students learn to search for an answer for their own questions based on scientific arguments?". Furthermore, to keep the questionnaire length manageable, the affective dimension was dropped. Four-point Likert-type scales were used. All student teachers enrolled in the iSTEM course in 2023-2024 were asked to fill in the online questionnaire at three-time instants: (1) before the iSTEM course (n=77), (2) after the first (design) part of the course (n=76), and (3) after the second (internship) part of the course (n=74). Pseudonymized responses were collected, in line with the ethics committee approval (G-2021-3888-R3).

Analysis

All analyses were executed in R v.4.2.3. (R Core Team 2023). Due to the limited sample size, construct validity was not yet established but will be assessed in the future when more data become available. Cronbach's alpha reliability scores were computed for each of the 10 expected factors, i.e. perceived importance and self-efficacy for each iSTEM principle. Per expected factor, mean factor scores were calculated, for which the median (and IQR) over participants were determined. Friedman tests were used to evaluate main effects of the test moment on each expected factor, and three post-hoc tests (Wilcoxon signed rank) were executed between time instants 1-2, 1-3 and 2-3. In order to maintain a significance level of 0.05, p-values were compared to a Bonferroni corrected cut-off value of 0.05/3=0.017.

Results

Results presented in Figure 1 and Table 1 indicate that there is a consistent V-like trend in the importance student-teachers attribute to the iSTEM principles before, during and after the iSTEM course. For most principles, self-efficacy increases during the course, with the largest increase during the first part of the iSTEM course.

Figure 1: Median scores over participants for perceived importance (IMP) and self-efficacy (SE). Error bars indicate interquartile ranges. INT = integration, PCL = real-world problems, IBL = inquiry, DBL = design, COO = teamwork.

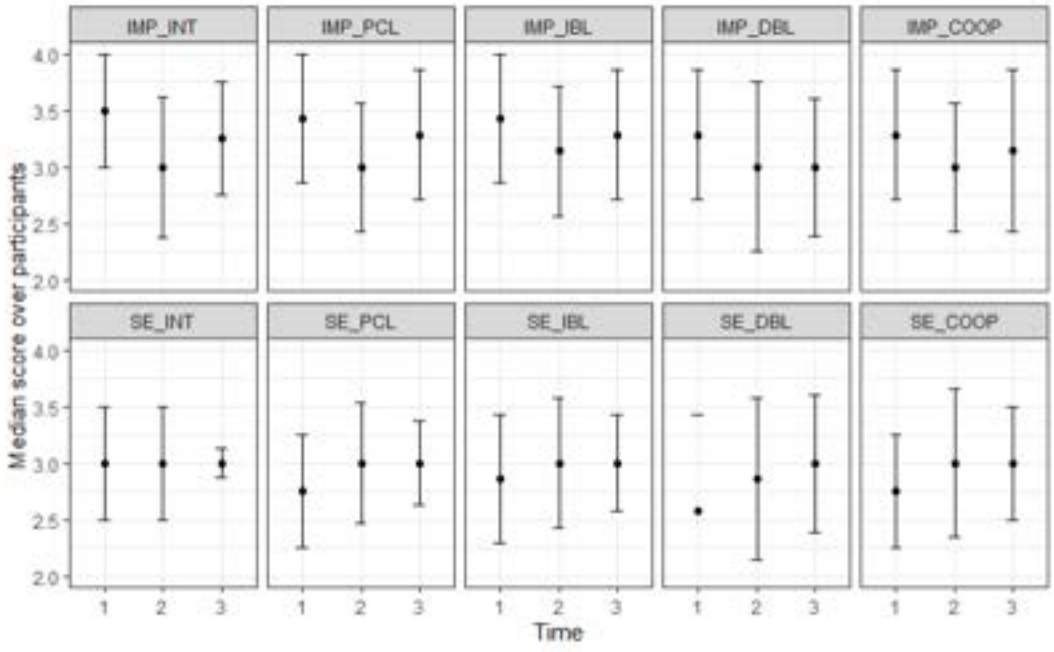


Table 1: Significant differences indicated in bold-face. INT = integration, PCL = real-world problems, IBL = inquiry, DBL = design, COO = team work.

	Perceived importance						Self-efficacy					
	Median			p-value between test moments			Median			p-value between test moments		
	1	2	3	1-2	1-3	2-3	1	2	3	1-2	1-3	2-3
INT	3.5	3.0	3.3	**<0.001**	0.573	**<0.001**	3.0	3.0	3.0	**0.005**	**<0.001**	0.113
PCL	3.4	3.0	3.3	**<0.001**	**0.002**	0.022	2.8	3.0	3.0	**<0.001**	**<0.001**	0.701
IBL	3.4	3.1	3.3	**0.001**	0.229	**0.014**	2.9	3.0	3.0	**<0.001**	**<0.001**	0.858
DBL	3.3	3.0	3.0	**0.002**	0.254	**0.010**	2.6	2.9	3.0	**<0.001**	**<0.001**	0.073
COO	3.3	3.0	3.1	**<0.001**	0.138	**0.006**	2.8	3.0	3.0	**<0.001**	**<0.001**	0.461

Discussion and conclusion

In this work-in-progress study researching student-teachers' attitudes, we tracked evolutions in students' perceived importance and self-efficacy towards five iSTEM principles, aiming to facilitate learners' transitions between STEM-subjects and beyond: integration, use of real-world problems, inquiry, design and teamwork. Preliminary results indicate that students attribute less importance to the five principles during an iSTEM course, than at the beginning, but that this effect disappears towards the end. We will collect qualitative data, via student interviews, attempting to explain this observation. Furthermore, students' self-efficacy towards each of the five principles seems to increase towards the teacher training program, with the most pronounced increase at the start of the iSTEM course. Although this study has limitations, such as the lack of control group and limited sample size, this is the first study investigating longitudinal changes in (student-)teachers' attitudes towards iSTEM. We will collect more data in the future and use this to assess construct validity of the adjusted (validated) questionnaire, confirm or refute the observed evolutions, and further investigate factors (prior experience, group composition, …) explaining (evolutions in) (student-)teachers' attitudes.

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ESERA 2025 Copenhagen

Transition From Secondary To University Level Education; Students' Skills Development For Math Education And Beyond

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This paper highlights the discussions from the first workshop of the Community of Learners Twente (C.O.L.T), emphasizing the importance of students' skills development to foster a smoother transition from high school to university, and academic success in STEM education. The findings and discussions focus on aligning educators observations and expectations from shared experiences.

Keywords: STEM, Transition, Community

Introduction

The Transition From K12 To Tertiary Education

The importance of discussions that focus on students' transition from high school to university cannot be overstated. Even though initiatives do exist addressing the topic, these remain isolated between high schools and universities. Research on this transition has been ongoing for over 20 years (Krause, 2005). Despite various initiatives to bridge the gap, studies (Y.Y. Hong, 2009) reveal that students often feel underprepared, and may experience a significant reality shock as they enter their first semesters. This mismatch between preparation and expectations can lead to declining academic standards or higher retention rates, as many students struggle to adjust during their first year (Brinkworth, 2009).

To begin with, the teaching methodologies in high school typically emphasize structured lesson plans, teacher-led instruction, and standardized assessments that often prioritize memorization and regurgitation of information. In contrast, university education frequently employs more diverse teaching approaches. Lectures may delve deeper into complex concepts and often emphasize the application of theoretical knowledge. This transition requires students to adapt quickly and develop strategies to engage actively with course material beyond passive absorption.

Moreover, university education places a premium on independent learning and self-directed study. Unlike the structured schedule of high school where classes are typically held daily and assignments are more predictable, university timetables may offer fewer face-to-face contact hours, leaving students with greater responsibility for managing their time effectively and sustaining motivation. The expectation to engage with supplementary readings, undertake independent research, and pursue personal academic interests demands strong self-regulation and organizational skills—areas where some students may initially struggle.

To continue with, the academic demands in university escalate significantly compared to high school. While high school curricula lay foundational knowledge across a broad spectrum of subjects, university courses delve deeper into specialized areas, demanding higher levels of analytical thinking, synthesis of information, and original thought. Additionally, the shift to university involves a cultural change in academic expectations. Students are expected to participate actively in class discussions, contribute to group projects, and seek out academic support resources proactively. This transition challenges students to develop interpersonal skills, collaborate effectively with peers, and navigate diverse learning environments where individual contributions significantly shape the collective learning experience.

Community Of Learners And C.O.L.T

In educational literature, the concept of a "community of learners" was first introduced in the 1980s and 1990s by Brown and Campione (Brown, 1994), and emphasizes on collaborative learning, where each member is actively engaging in constructing knowledge through interactions with peers and the environment. It set the foundations in shifting from traditional, teacher-centred education to a more social-constructivist approach, fostering a more interactive, and student-centred learning experience.

Under the principles of collaborative learning (Barton, 2010), where community members bring diverse experiences, expertise, and share best practices, the Community of Learners Twente (C.O.L.T) was established in 2024 to address the gaps identified between high school and university education. Initially, the community consisted mostly of math educators, but it soon expanded to include other disciplines such as physics and social sciences. This expansion transformed C.O.L.T into a comprehensive learning environment where STEM education is actively discussed and improved. It's a mutually beneficial scenario where high school teachers gain insights into the skills and knowledge students need for success in higher education, while university instructors benefit from valuable perspectives on strengthening foundational concepts and fostering critical thinking. Moreover, this collaborative community not only seeks to address immediate challenges but also aims to cultivate a supportive environment where educators can collaborate, learn from each other, and advocate for meaningful changes in STEM education. By doing so, we can better equip students with the skills, knowledge, and confidence needed to excel throughout their academic journeys and beyond. Ultimately, by fostering a culture of continuous improvement and innovation within this community, educators can collectively develop and refine approaches to mathematics education. This includes designing transition programs, integrating real-world applications into curriculum, and implementing assessment strategies that better reflect the expectations of university education.

This paper focuses on sharing discussions that took place during the first workshop of the community in October 2024.

Community Workshop 1

Bridging Gaps: From High School To University; Aligning Expectations And Observations For Student Success

The first workshop of the community took place in October 2024 at the University of Twente, with the participation of 4 high schools from the region of Twente. Both high school teachers and university instructors from diverse disciplines, including mathematics, physics and social sciences, came together to exchange ideas and insights.

Workshop Objectives

The purpose of the workshop was to investigate the transition from high school to university, with a focus on aligning educators' expectations with their observations of students' preparedness.

Workshop Design and Participants

To meet the outlined objectives, activities were carefully designed to encourage a collaborative and cross educational reflection, foster an active dialogue between educators at both levels, and identify key areas for student development.

The workshop tool placed in October 2024 for one and a half hours in a dynamic hybrid environment and involved high school teachers (2 present and 2 online due to teaching responsibilities), university educators (8), a guest PhD student, a session chair, and student research assistants (2).

Data Collection

Data was collected through a two-part question-and-answer activity, using sticky notes to collect teachers' input. The following questions were shared among the participants:

Question 1: What skills or knowledge do you expect students to have when transitioning from high school to university (both academically and behaviorally)?

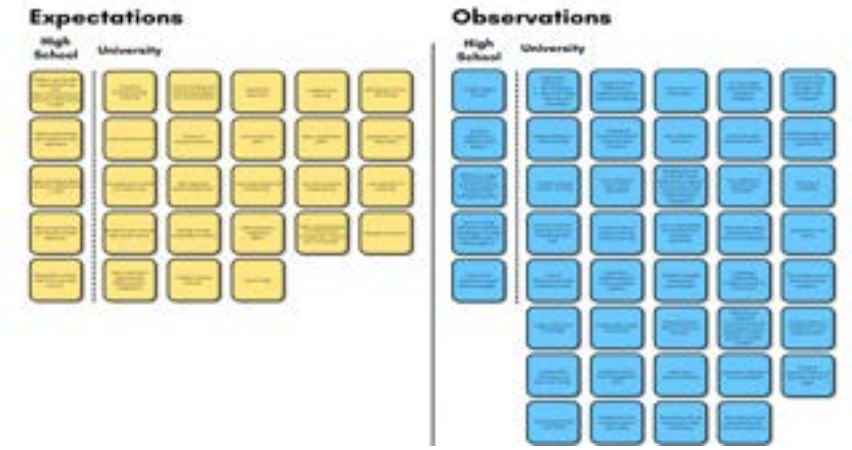
Clarification A: High school teachers were to describe their expectations for students upon graduation, while university teachers outline what they expect from incoming students.

Question 2: What do you observe about students' preparedness when they move from high school to university?

Clarification B: High school teachers were to share their perceptions of students' readiness at the end of high school, and university teachers to describe their observations of students' strengths and gaps when they first entered university.

Participants provided their responses on sticky notes, which were color-coded: yellow for "Expectations" and blue for "Observations." These responses were then placed in designated columns on a whiteboard (see Figure 1). The use of sticky notes enabled short and dynamic responses, fostering an open exchange of ideas. After the teachers completed their answers, two groups were formed (Yellow Team-Expectations, Blue Team-Observations) to discuss the findings before sharing them with the whole team.

Figure 1: Shared Expectations and Observations among educators.



Data Analysis

Once all responses were collected, it was asked by both groups to identify patterns in their provided answers. Through this process, three key themes were identified:

I. Skills

II. Foundational and Transferable Knowledge

III. Mindset and Attitude

The Venn diagram below summarizes the group findings.

Findings and Discussion

Finding a common ground between educators' expectations and observations was the goal of the comparison and discussion of the selected themes. The conclusions from the discussions are summarized below.

Figure 2: A Venn diagram comparing expectational and observational themes for students' skills, fundamental and transferable knowledge, and mindset and attitudes (Note: In green are the themes found in both).



Key Theme I: Skills

Students are expected to develop a range of skills as they transition from high school to university. These include information and media literacy, which involves searching, reading, and analysing literature, as well as tackling misinformation. Critical thinking and problem-solving skills, including logical reasoning, basic problem-solving for mathematics, and the ability to critically evaluate solutions and outcomes are also crucial. Furthermore, it is anticipated that students would acquire organizational skills, interpersonal (soft) skills, and teamwork and social skills, which include systematic approaches, effective communication, collaborative learning, and basic cooperation skills.

It is observed that students transitioning from high school to university often struggle with higher-order cognitive skills, critical thinking, problem-solving, and creativity. They experience a different, often faster pace at university, which requires adaptability. Additionally, students lack effective planning and time management skills, which are essential for balancing academic and personal responsibilities.

Key Theme II: Foundational And Transferable Knowledge

A solid foundation in mathematics and science concepts is essential for university success. Students are expected to have basic math skills, including polynomials, differentiation, and integration, although these concepts may not yet be well connected. The ability to apply these

concepts to broader areas is also important, highlighting the need for transferable knowledge. This foundational knowledge in mathematics and science forms the basis for further academic development and the ability to tackle more complex problems.

Shared observations among the teachers indicate that there is significant variation in students' foundational knowledge, particularly in basic math skills, which are essential for advanced studies. Students often struggle to apply learned concepts to real-world problems, highlighting the need for strong analytical and application skills. They also face challenges synthesizing multiple sources of information and transitioning from concrete to abstract mathematical reasoning.

Key Theme III: Mindset And Attitude

A proactive mindset and positive attitude towards learning are critical for students' success at university. This includes taking responsibility for their education, managing anxiety (especially in mathematics), and being able to plan and set up their study routines. Students are expected to be resilient, managing uncertainty effectively, and open-minded, showing a willingness to learn new things. Having confidence in themselves, engaging in their studies, and being able to ask for help from the right person are also important.

It is evident among observations that students often have a passive attitude towards learning and lack confidence in their abilities. They struggle with self-regulation, setting learning goals, and taking responsibility for their own education. Additionally, students have difficulty maintaining focus, are easily distracted, and often jump to conclusions without fully understanding problems. Building resilience and emotion regulation skills is also a challenge, as students struggle with dealing with failure and have a fear of mathematics.

Conclusion And Future Work

These series of workshops aim to establish a safe space where educators can share their best practices and discuss possible ways to address challenges that students face, especially on the transition from high school to university.

During the first workshop, the teachers from both levels shared their expectations, as well as their observations for the students ‘performance, behaviour and attitude towards learning. Group discussions revealed that many experiences overlap, emphasizing the importance of community and collaboration. These insights will be critical for the development of the upcoming workshops, ensuring valid and effective preparedness in promoting student success.

An important action point will be to ask students the same questions from both educational levels. This will ensure that the strategies developed reflect students' viewpoints as well.

As part of future workshops, the community will focus on developing strategies that promote a culture of respect for the learning process, and the educational environment. The goal is to help students recognize the value of owning their learning both for academic and personal growth as well. Furthermore, we aim to delve into discussions about student motivation, engagement, and self-regulation, student learning differences, inclusivity, and diversity. We aim to expand our community, host more voices, and foster a prosperous learning environment for students and educators.

Acknowledgement

The author gratefully acknowledges the contributions of the high school and university teachers of Twente region in the Netherlands, students, and invited guests who participated in the first community workshop, from which the results presented in this work were derived. Their active

engagement, constructive discussions, and collaborative efforts were essential to the successful implementation of this initial workshop and to the outcomes reported herein.

We also extend our sincere appreciation to all participants whose dedication and commitment supported the objectives of the first workshop series, which aims to promote scientific knowledge, community involvement, and educational collaboration. The continued support of educators, students, and community members is fundamental to the success of this ongoing initiative.

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Appendix

Participants

Community of Learners Twente (C.O.L.T)

University of Twente (UCT, PRE-U, ELAN, BMS)

Bataafs Lyceum (Hengelo)

Assink Lyceum (Haaksbergen)

Bonhoeffer College (Bruggestraat Enschede)

International School Twente (Enschede)

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PBL In STEM Across The Education Continuum In Denmark

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This paper outlines the principles and characteristics of problem-oriented and project-based learning (PBL) across educational levels in Denmark, focusing on authentic problems as a catalyst for reimagining pedagogical approaches in STEM education. The study examines PBL models in STEM from primary through higher education, highlighting the importance of easing transitions and fostering critical thinking, creative problem-solving, and collaborative competencies.

PBL, a student-centred instructional approach, engages students in interdisciplinary, experiential learning by addressing real-world problems. Originating in the 1960s in medical education, PBL was later adopted in engineering education in some universities, as well as technical high schools, evolving into various tailored versions. This paper compares PBL implementations in primary schools (Engineering in School), general and technical high schools (STX and HTX), and higher education engineering programs at Aalborg University (AAU), Roskilde University (RUC) and University of Southern Denmark (SDU).

Key findings emphasize the role of authenticity and student agency in problem-based STEM teaching. While primary and secondary education often present predefined problems to some degree, higher education engineering gradually introduces complex, ill-defined problems, emphasizing problem analysis and scientific evaluation of proposed solutions to enhance critical thinking. The paper highlights the need for integrated approaches and authentic assessment in STEM to enhance student motivation and learning outcomes, and it suggests directions for future research into the impact of cross-institutional collaboration on students' experiences of transition in STEM PBL practices.

Keywords: problem-based learning, educational transitions, STEM education

Introduction

Across educational levels, there is a growing emphasis on active, student-centred learning approaches such as problem-based and project-based, and inquiry-based learning aimed at enhancing student motivation, participation, and learning, particularly in STEM fields, often through authentic problem-solving. This article explores the characteristics of problem- and project-based learning (PBL) in STEM and examines similarities and variations in PBL models across the education continuum in Denmark. It emphasises the importance of articulating differences to support students' awareness and reflection on their diverse learning experiences and the progression in problem-oriented project work throughout the education system. Based on this analysis, the article provides recommendations for researchers, teachers, and educational institutions seeking to integrate more PBL into their teaching practices.

What Is PBL And Why Is It Relevant In STEM?

PBL is a student-centred instructional approach wherein students engage in interdisciplinary, experiential, and collaborative learning by addressing authentic problems. The concept of PBL emerged in the 1960s as a novel, application-oriented approach in medical education, aiming to better prepare students for practice (Hmelo-Silver, 2015). Denmark pioneered the field of PBL

within higher education outside medical education, with Roskilde University (RUC) in 1972 and Aalborg University (AAU) in 1974, particularly focusing on project-based PBL (Servant-Miklos & Spliid, 2017; Andersen & Kjeldsen, 2015). From the 1980s, PBL was also implemented in the newly established technical high school (HTX) in Technology and Engineering subjects, inspired by models from AAU and RUC (Jeppesen, 2021). Since then, more higher education institutions such as University of Southern Denmark (SDU) have implemented their own tailored versions of problem-oriented project work, particularly within engineering education, e.g. through case-based learning and semester projects centred around authentic problems (Giacalone, 2016). Recently, general high schools (STX) and primary education also increasingly focus on incorporating problems into teaching, for instance, in previous General Study Preparation ('Almen studieforberedelse') and later multi-disciplinary projects ('flerfaglige forløb') (EVA, 2021), along with initiatives like 'Engineering i Skolen' (Engineering in School, EiS, https://engineerthefuture.dk/undervisning/engineering-i-skolen/) and the 'Learning and Engagement through Authentic Projects focusing on Science' (LEAPS) schools (https://leapsskoler.dk/).

Various perspectives exist on what constitutes PBL, yet some consistent characteristics and principles include the following (Hmelo-Silver, 2004; Savery, 2015; Savin-Baden, 2007; Thomasson & Stentoft, 2020):

- A focus on complex, authentic, and exemplary (practice-oriented) problems with no single "correct" solution
- Students work in groups
- Students construct new knowledge through self-directed learning
- Teachers serve as facilitators

Authenticity And Agency In Problem-Based STEM Teaching

While PBL effectively incorporates current societal challenges, socio-scientific issues (SSI) in STEM (Ratcliffe & Grace, 2003), inquiry-based learning (IBL) emphasizes students' curiosity and connection to their local context and lived experience, fostering motivation and meaningful learning. Combining these approaches in STEM PBL is essential, as focusing solely on large-scale and 'wicked' problems such as the SDGs without actionable solutions can discourage students and contribute to climate anxiety (Darling, 2023). Therefore, we suggest combining the two in STEM (Figure 1) to ensure not only the authenticity and urgency of a given complex problem (e.g. reducing microplastics in the oceans), but also its perceived relevance, i.e. the connection to a student's individual curiosity, local community and personal science capital (e.g. reducing/recycling plastics in 'my own' household) (Nomikou, Archer & King, 2017).

This also highlights another important aspect: STEM PBL should encompass more than solely problem-solving. Solving complex problems requires significant creative, analytical, critical, and systems thinking, all competencies related to the ability to understand problems, namely, to identify, delimit, and formulate problems, rather than just solving them (Møller, 2022; Lavi & Bertel, 2024; Svabo et al., 2025).

PBL In STEM Across The Education Continuum

Below, comparable STEM PBL in primary school (Engineering in School - EiS), general (STX) and technical high school (HTX) and higher education (HE) engineering programs at AAU, RUC and SDU were used as basis for comparison (Figure 2) to illustrate different models, phases, and focus areas, and their emphasis at different levels in the education continuum.

Figure 1. Formulating authentic and meaningful problems in STEM.

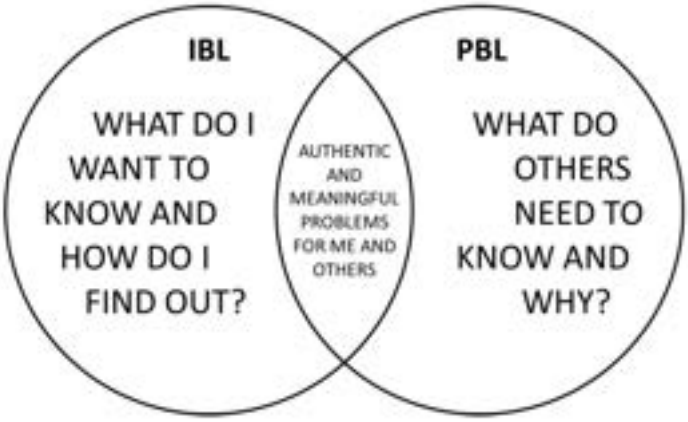
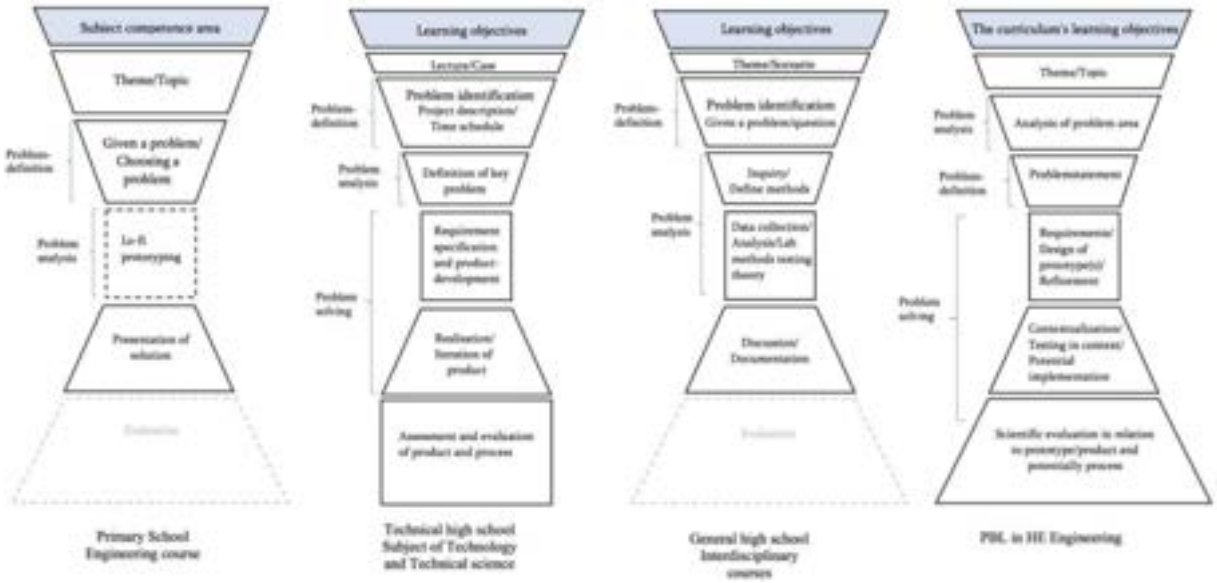


Figure 2. PBL variations across STEM education levels.



Problem Identification And Authenticity

The starting point for inquiry is often a theme or a delimited case. In EiS, HTX, and STX, problems are usually presented alongside the subject theme, with limited student involvement in defining them, although increasing attention is paid to students' problem identification skills in K12 (Møller, 2022; Jensen et al., 2025). In higher education (HE) engineering, student autonomy in defining problems varies, with problems becoming more complex at undergraduate and graduate levels. Authenticity motivates students across all levels, but the involvement of external stakeholders in problem identification and solution implementation increases in HE, especially at the master's level. While HE often struggles to integrate interdisciplinary collaboration in project work, even when the nature and complexity of a problem call for it (Bertel et al., 2022), primary and high schools have managed to formally integrate interdisciplinary learning (across science subjects) into their curricula to some extent.

Problem Analysis And Problem-Solving

While problem analysis and solving dominate in HTX and HE engineering, problem-solving is more limited in EiS and STX, where the focus is on designing lo-fi prototypes, research designs, or lab experiments to explore subject-specific knowledge and methods, rather than design processes and product development. HTX and HE engineering both emphasize problem-solving, but in HE, it is often part of problem analysis, with products serving as prototypes for rigorous

scientific evaluation. This evaluation, rather than the feasibility of the prototype, is the focus of summative assessment, although extracurricular entrepreneurship programs increasingly encourage students to explore product development as well.

Evaluation And Assessment

The evaluation of designs, solutions and learning processes varies across educational levels and between institutions. In EiS and STX, STEM PBL projects are generally short-term and often not formally assessed, though individual assessments of science-integrated projects are newly implemented in primary education. In HTX and HE engineering, STEM PBL projects are generally semester-long and assessed through group exams where students collaboratively elaborate on and defend their work. Knowledge-sharing and formative assessments, such as exhibitions, (public) pitch presentations and peer feedback in PBL schools like LEAPS, could potentially inspire STX, HTX, and HE engineering to involve stakeholders in authentic and contextual assessments of ideas and solutions.

Discussion And Future Work

This paper highlights the diverse implementations of problem-based learning (PBL) in STEM education across different educational levels in Denmark. By examining variations in STEM PBL approaches from primary school through higher education, we emphasize the importance of authentic, interdisciplinary, and student-centred learning experiences. Integrating real-world problems or socio-scientific issues (SSI) with students' personal curiosity and local context is crucial for creating authentic cases/scenarios, meaningful problems and actionable solutions, to foster motivation and increase student agency.

The role of students in defining and analysing problems varies across educational levels. While primary and secondary education often present predefined problems, higher education encourages engagement with more complex and ill-defined problems, essential for developing critical thinking and problem-solving skills. Interdisciplinary collaboration is more formally integrated into the curriculum at primary and secondary levels compared to higher education. However, HE institutions increasingly recognize the value of interdisciplinary approaches, particularly for addressing complex, real-world and ‘wicked’ problems.

Future work should include longitudinal studies to track the impact of PBL on student outcomes across and in transition between different educational levels. This will provide valuable insights into how PBL influences academic performance, motivation, and career readiness over time. Professional development opportunities and cross-institutional collaboration, such as those of the LabSTEM projects, should be encouraged to enhance a shared understanding of PBL, authentic assessment, and integrated STEM approaches and to support seamless transitions and progression in PBL practices through the education system. Policy changes and curriculum development supporting the widespread adoption of PBL in STEM education are also necessary. With the rapid developments in generative AI disrupting many disciplines, traditional assessments focusing on recalling factual knowledge are inadequate for assessing genuine skills and competencies. Therefore, guidelines and resources for facilitating interdisciplinary learning, authentic and formative forms of assessments (Dolin & Evans, 2017) are needed to better reflect the experiential, collaborative, and self-directed nature of PBL.

In conclusion, by addressing variations in STEM PBL, this paper calls for a continued focus on authentic, interdisciplinary, and student-centred learning experiences as well as ongoing dialogue and cross-institutional collaboration to improve STEM education and better prepare students for the challenges, transitions and transformations of the future.

Acknowledgement

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Bottom-Linked LabSTEM Learning Laboratories Across Denmark

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This article examines the application of the Laboratory Model within the LabSTEM projects in Denmark, exploring its role as a bottom-linked approach to research and development in STEM education. The Laboratory Model, a framework designed to integrate practice, education, and research, supports iterative collaboration between teachers and researchers. This dynamic methodology fosters competence development and innovative solutions to address transitions between STEM disciplines.
The study analyses three regional LabSTEM projects—South, North, and East—each tailored to local contexts and priorities. LabSTEM South emphasizes real-world orientation and integration of STEM disciplines through teacher-researcher collaboration. LabSTEM North focuses on "STEMification" via cross-institutional collaboration, emphasizing problem-based learning. LabSTEM East targets cross-level transitions, fostering problem-based and mathematical modeling learning to address subject integration challenges.
Findings highlight the Laboratory Model's adaptability and its capacity to empower teachers as agents of change, while generating practice-informed research insights. Collaborative learning emerged as a key theme across all three projects, enabling creativity, problem-solving, and sustainable teacher development. The study concludes that the Laboratory Model bridges the gap between research and practice by ensuring innovations are context-sensitive, widely applicable, and capable of transforming STEM education. These insights will inform future initiatives to enhance STEM education in Denmark and beyond, preparing students for future challenges and opportunities.

Keywords: STEM-teaching, laboratory-model, development

Introduction

In education, bridging the gap between research and practice remains a challenge, as educational innovations often struggle to be effectively integrated in classrooms (Coburn & Penuel, 2016). A key challenge in practice is developing integrated STEM education that facilitates transitions between disciplines while combining both conceptual understanding and practical application (Nadelson & Seifert, 2017). Transitions in STEM education involve teachers and students moving between disciplines, while ensuring a coherent learning experience (Kristensen et al., 2024). Given the increasing complexity of this challenge, there is a need for a development- and research model that is not only flexible but also capable of offering a range of possibilities to meet diverse educational needs. Research that integrates practice as both a site of inquiry and a source of learning might have the potential to address this gap. More recently, scholars have introduced the concept of bottom-linked research as a way to integrate the benefits of bottom-up and top-down approaches (Balslev, 2021). Bottom-up research starts from local practices and focuses on addressing practical challenges faced by practitioners, often prioritizing context-specific solutions over generalizability. In contrast, top-down research begins with broader theoretical frameworks or policy-driven agendas, which are then applied to practice, sometimes with limited sensitivity to local contexts. Bottom-linked research aims to bridge these approaches by

grounding inquiry in the realities of practice while also connecting findings to larger theoretical or strategic frameworks (Nielsen & Ryberg, 2011). This dynamic interaction ensures that research is both deeply relevant to practitioners and contributes to the broader knowledge base, addressing the limitations of purely bottom-up or top-down methodologies.

This article examines the 'Laboratory Model' (Svabo et al., 2024) in the LabSTEM projects as a bottom-linked approach that fosters inclusive, collaborative innovation.

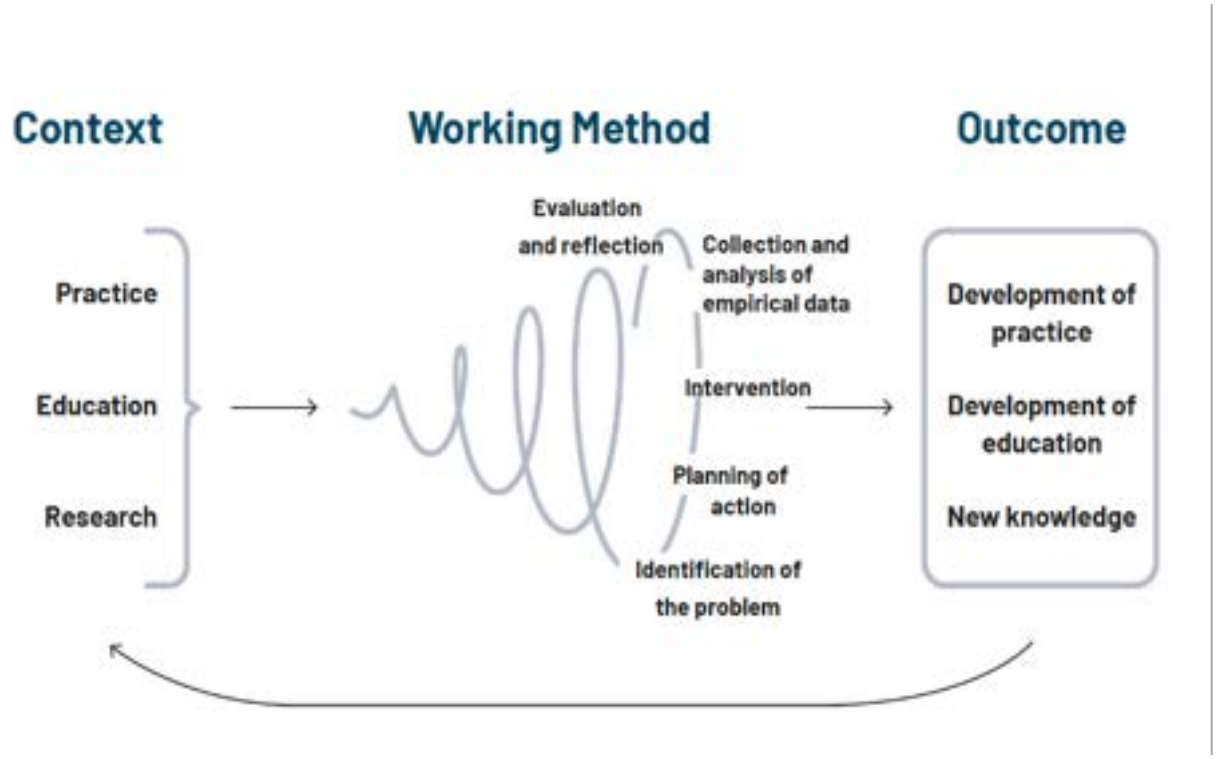
We address the question: *How is the Laboratory Model used in the research and development process to support transitions in the LabSTEM projects across Denmark, and what insights can be gained from its regional adaptations?*

The Laboratory Model

The Laboratory Model is a framework developed to enhance competence development in educational practices, particularly with a focus on transforming practice within schools and other educational settings. It was primarily developed by Claus Michelsen (Petersen et al., 2017) but further developed in (Svabo et al., 2024). The model is designed to foster collaborative research practices by integrating theoretical insights with practical application in a bottom-linked research approach. It emphasizes the role of both the teachers and the researchers as active participants in both the research and reform processes, allowing them to experiment, reflect, and refine their practices in real-world settings. The Laboratory Model supports an ongoing dialogue between theory and practice, thereby enabling continuous professional development through participation in transformative projects that target specific educational challenges.

The Laboratory Model connects three contexts: practice, education, and research, with the intended outcomes of practice development, educational development, and the creation of new knowledge (Figure 1).

Figure 1. The laboratory-model (Svabo et al., 2024).



The laboratory-model follows a circular and iterative change process: Starting at the bottom, the method consists of processes of 1) Identifying a problem, 2) Planning actions, 3) Intervening, 4) Producing data, and 5) Reflecting and evaluating.

Methods And Context - Three LabSTEM Projects

The LabSTEM projects, comprising three different initiatives across Denmark (South, North, and East), share a common goal of enhancing transition between the STEM-subjects in education. Central to these three projects is the Laboratory Model, which has been adapted to suit regional educational needs, local contexts, and the diverse backgrounds of participating teachers and researchers. By examining the different ways, the model has been employed in each region, we can gain insights into the adaptability of the Laboratory Model and its effectiveness in different educational settings.

The three LabSTEM projects, with LabSTEM South and North still ongoing, primarily target secondary school teachers.

In the following analysis, the three project leaders (who are also authors of this article) have described the application of the Laboratory Model across the different projects. This insider perspective provides a unique insight into the use and adaptation of the laboratory approach within various educational contexts.

LabSTEM South

LabSTEM South (2020–2025) focuses on developing and implementing STEM teaching based on core didactic principles. These principles are 1) a real-world orientation, 2) the integration of at least two STEM disciplines, 3) adopting a participant-centred teaching approach and 4) aligning with the subject-specific learning goals from the curriculum. In total, 250+ educators have been involved in the project's development activities.

In the circular and iterative change process of the Laboratory Model, the problem is defined (1) based on these principles and taken into account by the teachers. Planning the actions (2) takes place in established laboratories situated within the individual schools, where science and mathematics teachers collaborate with STEM-didactics researchers, often specializing in both mathematics and science education, to co-develop STEM teaching activities. In the collaborative process, researchers impose certain requirements which are based on STEM didactic principles. Reciprocally, teachers provide insights into practical context, including content preferences and pedagogical approaches tailored to their students' needs. This interplay fosters a rich exchange, integrating project-defined strategies with experiential knowledge, ultimately enhancing educational practices.

Teachers carry out the developed activities in their classes (3), while researchers observe and collect empirical data from these applications (4). This is followed by a collective reflection on the outcomes (5). The process culminates in a LabSTEM-conference that facilitates knowledge transition across laboratories, institutions, and educational levels. This dynamic supports both practice development and new research. LabSTEM South exemplifies the integration of practice and research, enhancing STEM teaching while deepening understanding of subject transitions.

LabSTEM North

LabSTEM North (2021-2025), focuses on developing a 'STEMification' framework, integrating principles and practices from problem-based learning (PBL), inquiry-based science education (IBSE), and creative platform learning (CPL) to foster students' curiosity and competences in STEM. The project adapts the Laboratory Model to emphasize cross-institutional collaboration in 'STEM Labs', where teachers from various subjects and/or educational levels work to co-create and STEMify their teaching, supporting transitions both between subjects and across educational levels in STEM. Initially, due to the covid-19 lockdowns, these STEM Labs were facilitated as online communities, through which teachers collaborated across disciplines and

institutions to co-create teaching materials and designs. However, initial results identified challenges with the online format, particularly due to external pressure and fatigue from emergency remote teaching at the time. Based on these experiences, the project transitioned to a blended model in 2022, combining online resources and face-to-face meetings which successfully enhanced participation and motivation.

In total, the project has engaged 90+ teachers from lower and upper secondary education, high school, vocational education, and higher education institutions in Northern Denmark, who work iteratively and collaboratively with integrating student-identified questions and authentic problems as points of departure for inquiry and problem-solving. Data is collected through observations and follow-up interviews to inform subsequent iterations. A yearly conference facilitates collective reflection and feedback sessions, along with workshops focusing on specific aspects of PBL and STEM to ensure continuous improvement and adaptation of local teaching practices.

LabSTEM East

LabSTEM East (2023-2024), concentrated on the development and application of teaching sequences within STEM education following certain core principles. Some of these are shared with LabSTEM South, including having a real-world orientation, the integration of at least two STEM disciplines, adopting a participant-centred teaching approach and aligning with the subject-specific learning goals from curriculum (in this case, the development of modelling competence). In addition, LabSTEM East adhered to a principle of problem-based learning, so teaching sequences focused on solving problems rather than, say, the exploration of a theme.

Two labs were established where teachers and researchers collaborated in ways quite similar to the labs of LabSTEM South where teachers and researchers were collaborating to co-develop teaching sequences based on the teachers' practical experiences and the researchers' didactical insights. One notable difference was the shorter duration of LabSTEM EAST due to the funding conditions, which meant that the labs in this project iterated the teaching sequences fewer times. One significant feature of LabSTEM East is that the labs brought together teachers from different educational levels focusing on the transition from lower secondary to upper secondary; when evaluating the labs, the teachers noted that this feature was highly beneficial. It allowed them to interact and inspire one another in developing their teaching sequences across levels.

Common Themes And Regional Adaptions - Analyses And Discussion

The Laboratory Model exemplifies a bottom-linked strategy by integrating the practical, context-sensitive strengths of bottom-up approaches with the broader, theoretical aspirations of top-down research. It fosters a dynamic interplay between practitioners and researchers, enabling co-creation and iterative refinement of STEM education practices. By grounding its methodology in real-world educational contexts and connecting these insights to larger frameworks, the Laboratory Model ensures that innovations are both deeply relevant and widely applicable. This approach empowers teachers as agents of change while providing researchers with a robust, practice-informed foundation for advancing STEM education theory and practice.

While the approaches in LabSTEM South, North, and East have been shaped by local contexts and priorities, several common themes have emerged across all three regions. One of the most significant of these is the emphasis on collaborative learning. Collaboration has been a cornerstone of the Laboratory Model. This collaborative environment has fostered creativity and problem-solving, allowing researchers and teachers to learn from each other and develop new ideas and solutions.

Each laboratory adapted to its research environment and school practices. The Northern and Eastern labs emphasized problem-based learning, reflecting their university's philosophy, while the Southern labs took a more open-ended approach with a focus on mathematics in STEM.

Adaptation to local context is an advantage of the Laboratory Model: it helps teachers become more independent over time. They build the skills needed to run their own "labs" in the future, even without researcher involvement. This aligns with the bottom-linked strategy by empowering teachers to take ownership and continue the work sustainably. Teachers who participated in previous years report continuing to use the project's developed activities.

Conclusion - Outcomes And Impact: The Laboratory Model As A Bottom-Linked Strategy

The Laboratory Model exemplifies a bottom-linked strategy by integrating the practical, context-sensitive strengths of bottom-up approaches with the broader, theoretical aspirations of top-down research. It fosters a collaboration between practitioners and researchers, refining STEM education practices. By grounding its methods in real-world contexts, it ensures innovations are relevant and applicable, empowering teachers as change agents and providing researchers with a solid foundation for advancing STEM education.

The Laboratory Model used across the LabSTEM projects has significantly impacted both researchers and participating teachers. For teachers, it provided opportunities to develop their ability to address transitions between subjects, while researchers gained valuable insights and produced research on these transitions. The regional variations in LabSTEM South, North, and East highlight the model's adaptability to diverse educational contexts and priorities. By fostering collaboration, inclusivity, and real-world connections, the laboratory model demonstrates its potential to transform STEM education, making it more relevant, engaging, and accessible to all learners. The learning from these projects will inform future STEM education initiatives and help prepare students to navigate and contribute to the challenges and opportunities of the future.

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Section: Views Of And Experience With Interdisciplinarity

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Self-efficacy Of Pre-service Teachers And In-service Teachers Towards Integrated Science And STEM

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The study focuses on comparing the levels of self-efficacy among pre-service teachers and in-service teachers in relation to integrated science and STEM education. The study is framed by an ongoing curricular reform in the authors' home country, which provides increased opportunities to emphasize the integration of educational content. The paper presents findings from a quantitative survey conducted through a structured questionnaire (N = 680). The results show that in-service teachers report substantially higher levels of self-efficacy than pre-service teachers, particularly in pedagogical content knowledge and in managing instructional activities. The biggest differences in content-related self-efficacy appear in mathematics and in the ability to explain natural phenomena. Both groups demonstrate comparatively low self-efficacy in the practical implementation of STEM integration and in adapting integrated content to diverse age groups. Based on these findings, the study identifies priority areas for strengthening support in pre-service teacher education and outlines strategies to enhance competency development among both practicing teachers and teacher education students.

Keywords: self-efficacy, STEM education, science education

Theoretical background

In the Czech Republic, national curricular documents are currently undergoing revision, with increasing attention to opportunities for integrating educational content and fostering cross-curricular connections. In the fields of science and mathematics education, integration is frequently discussed through the lens of science education (as Biology, Physics, and Chemistry are traditionally taught as separate subjects in the Czech Republic) and through the STEM approach (see Sanders, 2009; Siekmann & Korbel, 2016). Both forms of integration aim to respond to the needs of a globalized world, emerging economic challenges, issues of sustainability, and the overarching emphasis on competencies for the 21st century (UNESCO, 2019).

Although the previous curriculum framework allowed schools to integrate subject areas (Hejnová, 2011), only a small number of schools took advantage of this opportunity. The newly designed curriculum provides schools with model school framework programmes in which integration has already been implemented, offering school leaders and teachers a more accessible source of inspiration. Every school has to design own school framework programme but they can decide if the follow traditional subject-related model, integrated model or thematic model. The subject Příroda a já ("Nature and Me"; designed by a team that included authors of this contribution) is the example from integrated model school framework programme (NPI ČR, 2025). This subject integrates content from Biology, Physics, and Chemistry at ISCED 2 level, thus corresponding to international conceptions of integrated 'science'

Implementing a high-quality integrated approach requires teachers to possess a sufficient level of self-efficacy and pedagogical beliefs (Chen et al., 2020). Teachers must not only be confident in their content-matter knowledge but also capable of carrying out appropriate pedagogical

transformations to ensure that tasks and instructional content are aligned with the abilities and developmental characteristics of learners (An, 2017). Both Czech studies (e.g., Koldová, Rokos, & Hašková, 2022; Patoková et al., 2024) and international research (e.g., Yang, Wu, & Li, 2023; Margot & Kettler, 2019) highlight that teachers often lack methodological support during pre-service preparation as well as in their in-service practice, whether in the form of professional development courses or examples of effective instructional practice. As a result, their self-efficacy for implementing STEM in classroom settings tends to be low.

The concept of self-efficacy is grounded in Bandura's (1997) theoretical work, which stresses that individuals' beliefs in their capability to successfully perform a task substantially influence their actual performance. In the educational context, teachers with higher levels of self-efficacy tend to feel more competent to adopt innovative methods and technologies, leading to improved instructional effectiveness (Tschannen-Moran & Hoy, 2001; Klassen & Chiu, 2011; Zakariya, 2020). Within STEM education, teacher self-efficacy – together with content knowledge and pedagogical content knowledge across integrated domains – constitutes a critical factor in realizing effective integrated instruction (Yang et al., 2023; Geng et al., 2019; Gunning & Mensah, 2011; Smetáčková & Páchová, 2025; Zakariya, 2020).

A variety of studies address teacher self-efficacy within individual STEM disciplines (e.g., Nipyrakis, Stavrou, & Avraamidou, 2024; Chen et al., 2020; Çiftçi et al., 2020; Park et al., 2017; Simoncini & Lasen, 2018), yet comprehensive investigations in the Czech educational context remain limited. This research study builds on and adapts existing validated instruments for assessing self-efficacy among in-service teachers and pre-service teachers, thus enabling international comparability while simultaneously addressing a significant research gap within Czech education.

Existing evidence on the most common barriers and opportunities for implementing integrated instructional approaches in educational practice (Rokos & Koldová, 2024; Patoková et al., 2024) suggests that strengthening the self-efficacy of both in-service teachers and pre-service teachers for STEM-based instruction will require a combination of complementary approaches and strategies targeting their pedagogical, disciplinary, and methodological skills. At the same time, it will be essential to prepare pre-service teachers in ways that equip them with the necessary competencies and a sufficient level of self-efficacy for integrated instruction, while also providing in-service teachers with robust professional, methodological, and didactic support (Koldová, Rokos, & Hašková, 2022; Rokos & Koldová, 2024).

Methodology

The paper presents the initial phase of a broader research project examining the self-efficacy of pre-service teachers and in-service teachers. The results reported in this contribution are based on a quantitative survey conducted using a structured questionnaire and are complemented by selected insights from the subsequent qualitative phase of the study. The aim of the quantitative investigation was to address the following research questions: (1) What is the level of self-efficacy among pre-service teachers and in-service teachers in relation to integrated science instruction and the STEM approach? (2) To what extent do perceptions of self-efficacy differ between these two groups? and (3) What forms of support for enhancing self-efficacy would the respondents prefer?

Research Instrument

The research instrument was adapted from several established tools, specifically the STEM Teaching Efficacy Belief Instrument (STEBI; Riggs & Enochs, 1990; Deehan, 2017), the T-STEM Science Scale (Unfried et al., 2022), the Teachers' Sense of Efficacy Scale (TSES;

Tschannen-Moran & Hoy, 2001), and the STEM Teaching Self-Efficacy Scale (STSS; Yang et al., 2023). To ensure validity and reliability, several steps were undertaken: forward–backward translation and cultural adaptation, assessment of content validity, split-half reliability testing (80/20), and calculation of Cronbach's α, which exceeded 0.7 for all items.

In total, the instrument comprised 49 items divided into five sections:

1) Demographic data: information about respondents (four multiple-choice items and three open-ended questions);
2) Integrated science teaching: one open-ended question and ten statements;
3) Integrated STEM teaching: one open-ended question and ten statements;
4) Self-efficacy related to integrated pedagogical content knowledge: ten statements;
5) Self-confidence and motivation to implement integrated teaching: ten statements.

All statement items were rated on a five-point Likert scale (1–5), where 1 corresponded to option 'strongly agree'.

Characteristics Of The Research Sample

The first group of respondents consisted of pre-service teachers from the Faculty of Education, University of South Bohemia in České Budějovice. In total, 100 responses were collected, including 84 female and 16 male participants. All respondents were master's degree students who had completed at least two courses in subject didactics and were studying at least one specialization within the STEM disciplines. Data collection for the pre-service teacher group took place between 2023 and 2024.

The second group consisted of in-service teachers, with 580 participants in total (458 women, 122 men). Among these respondents, 403 were biology teachers, 147 chemistry teachers, 61 physics teachers, 139 mathematics teachers, 25 informatics teachers, and 90 geography teachers. (Note: In the Czech Republic, teachers are typically trained in two-subject combinations; therefore, the sum of subject specializations exceeds the total number of respondents, as some teachers qualified in combinations such as biology–mathematics.)

Regarding teaching experience, the sample included novice teachers with fewer than four years of practice (33.96%), experienced teachers with four to twenty years of practice (44.66%), and highly experienced teachers with more than twenty years of practice (21.38%).

Focus Groups

Responses to the third research question were obtained primarily from the qualitative phase of the study, which involved semi-structured interviews with selected respondents and discussions conducted in focus groups. The interviews focused on interpreting the results of the quantitative survey and, in particular, on participants' personal perceptions of their own self-efficacy. Their purpose was to extend and deepen the findings emerging from the quantitative phase.

In addition, the interviews explored examples of situations in which respondents felt confident or uncertain with regard to the integration of educational content, key challenges they encountered, strategies they used to manage uncertainty, approaches and methods they believed would support their practice, and the perceived implications for their professional development. Four focus group sessions were conducted in total – two with pre-service teachers and two with in-service teachers. Each focus group involved 20 voluntary participants. All sessions followed a pre-defined discussion protocol and were facilitated by the same member of the research team. The discussions were audio-recorded to allow for subsequent transcription.

Data Analysis

For the quantitative dataset, an aggregation metric was applied in which positively valenced responses (strongly agree and agree) were combined, as were negatively valenced responses (strongly disagree and disagree). Subsequently, item-level comparisons between the two respondent groups were conducted using a two-tailed z-test for the difference between proportions (normal approximation without continuity correction). All calculations were based on the actual number of agreement responses in each group. p-values were rounded to four decimal places, and statistical significance was set at $p < 0.05$.

For the focus groups, transcripts of each session were analysed using thematic coding (Kusnir, 2025). Two researchers independently coded the data, and their outputs were compared. The analysis was conducted using Atlas.ti software. In cases where discrepancies between coders were identified, the coding was repeated by a third independent researcher.

Results

Given the unequal sample sizes across the two respondent groups, all results are presented in relative frequencies.

Integrated Science

Pre-service teachers reported the highest level of agreement in relation to confidence in their biology content knowledge (70% agreement; 17% neutral; 13% disagreement), whereas the lowest confidence was observed in physics content knowledge (13% agreement; 16% neutral; 71% disagreement). In-service teachers showed the highest agreement for the statement "I am constantly looking for better ways to teach science topics" (89.7% agreement; 6.4% neutral; 4.0% disagreement), alongside a similarly high level of confidence in their biology content knowledge (75.3%). Their lowest agreement also appeared in relation to physics content knowledge (29.8%).

When comparing the two groups' confidence across the content areas integrated within the science approach (biology, physics, chemistry), in-service teachers were markedly more confident than pre-service teachers (46.0% vs. 24.0% agreement). Among pre-service teachers, disagreement prevailed (49.0%) on items relating to content knowledge. Both groups felt confident in biology (75.3% vs. 70.0% agreement). In physics, confidence remained low for both groups (29.8% vs. 13.0% agreement), although in-service teachers showed a 16.8 percentage-point (p.p.) higher agreement than pre-service teachers.

Unsurprisingly, the largest differences favouring in-service teachers were found in self-efficacy related to pedagogical content knowledge and didactic skills, including classroom interaction, reflection, and the ability to clearly explain scientific concepts. For example, the statement "When teaching science, I feel confident welcoming students' questions" yielded 63.4% agreement among in-service teachers compared to 24.0% among pre-service teachers (+39.4 p.p.). For the statement "I can clearly and comprehensibly explain natural laws and phenomena", agreement was 71.9% vs. 39.0% (+32.9 p.p.). These items were subsequently identified in the item-level analysis as those showing the largest differences between the two respondent groups (see Table 2 below).

Integrated STEM

In the context of integrated STEM, the differences between the two respondent groups are even more pronounced. Pre-service teachers reported very low confidence on both items related to mathematics content knowledge: mathematics content knowledge: 7.0% agreement; 20.0% neutral; 73.0% disagreement; application of mathematical principles: 7.0% agreement; 25.0% neutral; 68.0% disagreement. In-service teachers expressed substantially higher confidence on the same items: mathematics content knowledge: 46.7% agreement (20.0% neutral; 33.3%

disagreement); application of mathematical principles: 44.7% agreement (20.2% neutral; 35.2% disagreement). These differences amount to +39.7 and +37.7 percentage points, respectively, in favour of in-service teachers.

Among in-service teachers, the highest level of agreement was recorded for the statement "I am confident in my science-related knowledge" (62.1%). Conversely, agreement was extremely low for "I have sufficient knowledge across all STEM disciplines" (12.6%). Pre-service teachers likewise showed low agreement on this item (10.0%), indicating a general lack of confidence in relation to the cross-disciplinary breadth of STEM.

Interestingly, the pattern reverses for the statement "I have sufficient knowledge of technologies used in STEM education": pre-service teachers reported 39.0% agreement, compared with only 14.1% among in-service teachers (−24.9 p.p., in favour of pre-service teachers). However, in-service teachers showed slightly higher agreement on "I am confident in the field of technical education" (25.9% vs. 15.0%), although overall confidence in this domain was low in both groups, with disagreement or neutrality prevailing.

For the statement "I am able to prepare lessons that integrate STEM content", agreement was low and nearly identical in both groups (21.0% among pre-service teachers and 20.0% among in-service teachers; −1.0 p.p.). A similar pattern was observed for "I am able to adapt STEM content for students of different age groups while respecting the school's curriculum framework" (27.0% vs. 25.3%; −1.7 p.p.). These results suggest that practical integration and differentiation of STEM content remain challenging areas across both respondent groups.

Welcoming students' questions in the STEM context again showed higher agreement among in-service teachers (17.4% vs. 9.0%). However, the absolute levels of agreement were low in both groups and accompanied by high neutrality or disagreement, which aligns with the patterns observed in the integrated science results.

Findings From The Focus Groups

To address the identification of preferred forms of support for enhancing self-efficacy (see Research Question 3: Which forms of support would respondents prefer?), four focus groups were conducted – two with pre-service teachers (N = 40) and two with in-service teachers (N = 40). Pre-service teachers expressed a preference for structured mentoring (that means collaboration with an assigned mentor during their induction into school practice), continued opportunities for cooperation with colleagues teaching other science subjects, and receiving feedback from more experienced teachers (e.g., through peer observations).

In-service teachers most frequently selected professional learning communities, sharing of good practice, and the possibility of consulting colleagues who teach the same subjects. Both groups agreed on the importance of accessible professional development courses that would explain not only the principles of integration but, crucially, also present concrete examples of good practice and actionable teaching activities.

When related to Bandura's theory of self-efficacy sources (see Bandura, 1977; Palmer, 2006; Evans, 2015), it is evident that pre-service teachers most strongly value vicarious experiences, whereas in-service teachers prefer mastery experiences as the most effective source of building their confidence. In-service teachers described vicarious experiences primarily as stimuli or motivation for designing and implementing their own teaching activities, which would then allow them to strengthen their self-efficacy through personal mastery. Only a small number of respondents in both groups identified social persuasion (e.g., encouragement from school leadership or colleagues) as a significant source of their self-efficacy.

Overall Summary

The aggregated overview of agreement, neutral responses, and disagreement across items indicates that in-service teachers report substantially higher levels of alignment with statements related to science teaching; their disagreement rates are less than half those observed among the pre-service teacher group (Table 1). This pattern is consistent across all items examined. In the STEM context, overall confidence and the self-reported ability to integrate content are lower than in the integrated science context, although in-service teachers again achieve higher values than pre-service teachers.

Table 1. Aggregated comparison of agreement, neutrality, and disagreement across research areas for both respondent groups.

Area	Pre-service			In-service		
	agreement	neutral	disagreement	agreement	neutral	disagreement
Science	36.6%	22.8%	40.6%	60.3%	21.7%	18.0%
STEM	19.7%	21.4%	58.9%	31.3%	29.1%	39.6%

Within the item-level analysis, it was possible to identify statements showing the largest differences between the two respondent groups. Table 2 (next page) summarizes the five largest differences in favour of in-service teachers within the integrated science domain (items labelled Sci) and the five largest differences within the integrated STEM domain (items labelled STEM). The overall ordering in the table is sorted in descending order according to the magnitude of the percentage-point difference.

Discussion, Limitations, And Implications

The data show that while content knowledge is strongest in biology and most challenging in physics for both respondent groups, this pattern is consistent with international findings highlighting uneven teacher confidence across STEM disciplines (Margot & Kettler, 2019; Yang, Wu & Li, 2023). The relatively positive results in biology-related self-efficacy are strongly influenced by the fact that biology was the most frequently represented specialization in both groups (pre-service teachers: 88.0%; in-service teachers: 69.5%). Thus, a higher degree of confidence in biology content knowledge is expected, confirming the role of disciplinary preparation in shaping domain-specific self-efficacy (Klassen & Chiu, 2011).

In the STEM domain, in-service teachers demonstrate relatively stronger confidence in mathematics and basic mathematical principles, whereas integrated STEM and the technological dimension represent more problematic areas. Interestingly, pre-service teachers report higher confidence specifically in technologies, yet this does not translate into confidence in integrated didactic application – as reflected in the consistently low agreement for items on preparing integrated STEM lessons and adapting STEM content. This pattern suggests that while pre-service teachers are exposed to modern technologies during their training, they do not feel sufficiently confident to implement them effectively in practice (An, 2017). In contrast, in-service teachers often develop their use of technologies gradually through teaching experience or through consultation with more technologically advanced colleagues. Overall, they also show relatively lower confidence unless they hold formal qualifications in informatics, physics, or technical education.

Pedagogical self-efficacy (e.g., classroom interaction, explaining phenomena, supporting conceptual understanding, fostering student interest) consistently shows higher values among in-service teachers, aligning with self-efficacy theory (Bandura, 1997) and extensive empirical

evidence (Tschannen-Moran & Hoy, 2001; Zakariya, 2020). These differences are logical, given that teachers develop key competencies predominantly through practical experience, whereas pre-service teachers have limited opportunities to cultivate them (Çiftçi et al., 2020).

Table 2. Item-level analysis – largest differences between responses of pre-service and in-service teachers.

Item	Agreement (%)		Difference (p.p.)	z	p
	pre-service	in-service			
STEM4: Confidence in mathematics	7.0	46.7	+39.7	7.46	$p < 10^{-5}$
Sci7: Welcoming students' questions	24.0	63.4	+39.4	7.37	$p < 10^{-5}$
STEM9: Application of basic mathematical principles	7.0	44.7	+37.7	7.13	$p < 10^{-5}$
Sci10: Seeking better ways to teach science	55.0	89.7	+34.7	8.86	$p < 10^{-5}$
Sci5: Clear explanation of natural laws and phenomena	39.0	71.9	+32.9	6.46	$p < 10^{-5}$
STEM1: Confidence in science-related knowledge	30.0	62.1	+32.1	5.99	$p < 10^{-5}$
Sci8: Helping students who do not understand a concept	32.0	62.9	+30.9	5.80	$p < 10^{-5}$
Sci9: Increasing students' interest in science	41.0	65.7	+24.7	4.70	$p < 10^{-5}$
STEM2: Confidence in using technologies in teaching	32.0	44.5	+12.5	2.33	0.0198
STEM3: Confidence in technical education	15.0	25.9	+10.9	2.34	0.0193

Legend: Full wording of statement items: **STEM4**: I am confident in my knowledge of mathematics.; **Sci7**: When teaching science, I feel confident welcoming students' questions.; **STEM9**: I understand basic mathematical principles and can apply them in teaching in alignment with the school curriculum.; **Sci10**: I continually strive to find better ways to teach science topics.; **Sci5**: I can clearly and comprehensibly explain natural laws and phenomena.; **STEM1**: I am confident in my science related knowledge.; **Sci8**: When a student struggles to understand a scientific concept, I feel confident that I know how to help them better understand it.; **Sci9**: I know what to do to increase students' interest in science.; **STEM2**: I am confident in my knowledge of using technologies in teaching and introducing them to students.; **STEM3**: I am confident in my knowledge of technical education.

These findings are further confirmed by the results from the focus groups, where the groups identified the relevant sources of self-efficacy (see Bandura, 1997; Palmer, 2006; Evans, 2015). Pre-service teachers demonstrated a strong need to gain confidence and practical experience through support from experienced educators and by observing successful integrated instruction. This preference reflects their lower professional autonomy and their reliance on vicarious experiences. Conversely, in-service teachers prioritized professional communities and peer consultation, appreciating opportunities to share concrete experiences and solve issues emerging from everyday practice, reflecting their emphasis on mastery experiences. These conclusions are consistent with selected international studies (e.g., Palmer, 2006; Rice & Roychoudhury, 2003).

Based on the data, several practical recommendations and directions for further investigation can be formulated. It is evident that in the context of integrated STEM, the mathematical component requires targeted support, particularly for pre-service teachers. One possible approach is the inclusion of didactically structured activities that explicitly link mathematical content with science subjects, accompanied by formative assessment focusing on mathematical reasoning and the identification of analogies (Samková, Rokos & Vízek, 2025).

There is also a need to place greater emphasis on the development of interactive teaching skills within the science context, such as preparing for effective classroom discussion, facilitating student questions, and explaining scientific phenomena with a focus on conceptual understanding of integrated content. In everyday practice, in-service teachers possess considerable tacit knowledge and classroom-based expertise that could be more systematically incorporated into

pre-service teacher preparation.

Regarding technology, for pre-service teachers it is important to transform technological confidence into competence in integrated instruction – for instance, through the design of lessons requiring connections across S-T-E-M components, rather than relying solely on isolated uses of ICT (see also Unfried et al., 2022). Insights from the focus groups indicate that both pre-service and in-service teachers would welcome a broader range of professional development courses introducing effective approaches to integration and offering concrete examples of good practice.

The influence of the sample composition – particularly the high proportion of respondents specializing in biology – could be addressed by conducting a follow-up substudy comparing only respondents with a biology background. Such a comparison would also be appropriate given the almost identical sample sizes of pre-service and in-service teachers within this specialization.

Conclusion

The results confirm that in-service teachers consistently report higher self-efficacy than pre-service teachers, particularly in the areas of pedagogical skills and science content knowledge. The most substantial differences relate to confidence in mathematics and the ability to apply mathematical principles, which represents a critical challenge for pre-service teacher preparation. Both groups exhibit low levels of confidence in the practical integration and differentiation of STEM content, indicating a clear need for targeted methodological support. Pre-service teacher education should therefore be strengthened through didactically structured activities that link mathematics with science subjects, an emphasis on the integrated context of science education, and the presentation of examples of good practice from schools where integrated science or STEM instruction has already been implemented. It is also essential to foreground pedagogical strategies for making disciplinary content accessible and to provide both pre-service and in-service teachers with opportunities to build stronger confidence in understanding STEM-related disciplinary content – particularly for those who have not formally studied these subjects. Such support should prioritise knowledge directly relevant to the primary and lower-secondary curriculum.

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Teachers' Experiences With STEAM Outdoor Education Training: Challenges And Opportunities

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Despite recognition of outdoor learning's potential to enrich STEAM education, its sustained implementation in schools remains limited by teacher training gaps, resource constraints, and cultural resistance. This study explores in-service teachers' experiences following completion of a postgraduate STEAM Education programme featuring a dedicated STEAM Outdoor Education module. Thematic analysis using Braun and Clarke's (2006) six-phase framework was applied to semi-structured interviews with seven Portuguese primary and secondary teachers. Eight themes emerged: (1) professional identity building around STEAM outdoor; (2) training quality; (3) transformation toward outdoor-integrated practices; (4) student impacts; (5) institutional barriers (time, self-funding); (6) peer collaboration versus resistance; (7) families and community role; and (8) need for ongoing professional support. Findings reveal training's efficacy in building confidence and interdisciplinary skills, tempered by school-level sustainability challenges. Implications include redesigned primary-focused programmes with formalized mentoring and institutional partnerships to scale adoption.

Keywords: Outdoor Learning, STEAM Education, Teacher Professional Development

Introduction

Across the globe, we are facing rapid changes and transformations that demand professionals to continually update their knowledge in order to address a range of pressing issues, including environmental, food, energy, and healthcare challenges (Kelley & Knowles, 2016). In response to this, there has been a growing interest in an educational approach that fosters the integration of multiple disciplines—Science, Technology, Engineering, Arts/Humanities, and Mathematics (STEAM)—which has proven to be highly beneficial for the learning and development of children and young people (Dejarnette, 2012; Thibaut et al., 2018). This approach is viewed as crucial in nurturing students' interest and engagement in various subject areas from an early age (Haas et al., 2021; Khwaengmek et al., 2021; Jamali et al., 2022; Molina-Ascanio et al., 2023). However, achieving this requires adopting an integrative STEM (Science, Technology, Engineering, and Mathematics) perspective, which emphasizes an interdisciplinary approach to content, and encourages problem-solving, inquiry-based learning, design thinking, and collaborative learning (Thibaut et al., 2018).

STEM education first emerged in the United States in the 1990s, initially coined as SMET (Science, Mathematics, Engineering, and Technology). Its evolution into STEAM reflects a broader understanding of the educational process, recognizing the value of the arts, social sciences, and humanities in fostering creativity and offering a more holistic view of the world (English, 2016; Sanders, 2009). Numerous studies have highlighted the advantages of STEAM education. Conradty and Bogner (2018) emphasize the importance of its interdisciplinary approach in fostering social and emotional skills, while Stephenson et al. (2022) underscore the value of connecting theory with practice as a key benefit of this model. Providing students with a solid grounding in STEAM subjects is essential not only for preparing them for future careers but also for equipping them with the tools to apply scientific knowledge in their everyday lives, thus honing their critical thinking and problem-solving abilities (Metz, 2014). STEAM activities

are particularly effective in stimulating creativity and collaboration due to their practical, hands-on, and exploratory nature (Malecha, 2020), which is why they are widely recommended at all educational levels (Campbell & Speldewinde, 2022; Correia & Martins, 2023).

Outdoor education, as a pedagogical method, acknowledges the potential of natural spaces—such as gardens, parks, and schoolyards—as ideal environments for meaningful learning. Through active engagement with nature, students have the opportunity to develop motor, cognitive, and emotional skills in a holistic manner (Molina & Tasiopoulou, 2023). Numerous studies highlight the benefits of outdoor learning, including increased motivation to learn, the development of interpersonal skills, and improved academic performance (Browning & Rigolon, 2019; Waite et al., 2016). Has also been gaining prominence, particularly with growing concerns over obesity and sedentary lifestyles among young people (WHO, 2016), as well as evidence that connecting with nature enhances students' physical and mental well-being by reducing stress and promoting physical activity (Louv, 2005; Reese, 2018). Considering that outdoor learning in environments where children can engage with nature plays a crucial role in fostering exploration, investigation, observation, debate, hands-on activities, and sensory reconnection with nature (Molina & Tasiopoulou, 2023; Van Dijk-Wesselius et al., 2020), it serves as a valuable resource that can complement the STEAM approach effectively.

Despite widespread recognition of the potential of outdoor learning by many educators (Erdem, 2018), this approach remains underutilized in schools (Feille & Nettles, 2019; van Dijk-Wesselius et al., 2020). In comparison to other educational settings, schoolyards are used less frequently for pedagogical purposes (Larsson & Rönnlund, 2021). Several studies have highlighted barriers that hinder the adoption of outdoor learning, including teachers' lack of knowledge and confidence, safety concerns, curricular constraints, and organizational pressures within schools (Bentsen et al., 2013; Dring et al., 2020; Dyment, 2005; Ernst, 2007; Fang et al., 2022; van Dijk-Wesselius et al., 2020). In this context, teacher training plays a pivotal role (Caballero-Blanco & Lasaga-Rodriguez, 2021; Dyment, 2005; Larrea et al., 2022; Pitiporntapin et al., 2023; Tan & Atecio, 2016; Tuuling et al., 2019).

Given the significant potential of outdoor learning to connect STEAM content with real-world experiences—enhancing both the meaningfulness of learning and the holistic development of children and young people—an exploratory study was conducted to address the lack of concrete data on teachers' perceptions and training needs regarding the pedagogical use of outdoor spaces (Correia et al., 2024). This study aimed to assess how kindergarten and primary school teachers (1st and 2nd cycles) from a group of schools in Portugal perceive the educational value of outdoor spaces and to identify the competencies and training they consider essential for implementing a STEAM outdoor approach. Findings from the questionnaire indicate that teachers recognize outdoor spaces as valuable for STEAM education, with play, expression, and well-being emerging as the most emphasized dimensions. However, interdisciplinary activities integrating multiple STEAM subjects were infrequent, primarily due to the rigidity and time constraints of the curriculum, as reported by participants. Teachers highlighted the need for professional development in outdoor pedagogy, curriculum integration, and interdisciplinary teaching. While most educators reported having no formal training in outdoor education, they expressed a strong willingness to participate in training programmes (Correia et al., 2024). To fully leverage the pedagogical potential of outdoor learning within the STEAM framework, it is essential to provide targeted training opportunities that equip teachers with the skills and strategies necessary to integrate outdoor spaces effectively into their teaching practices.

Previous research highlighted the critical need to equip in-service teachers with the knowledge, skills, and opportunities required to implement outdoor teaching in a dynamic and

interdisciplinary manner, maximizing the potential of outdoor education (Correia et al., 2024). To build on these findings, further research and discussion are necessary to better understand the knowledge, experience, and training in-service teachers need to effectively integrate STEAM education into outdoor settings. Building on this prior research, some in-service teachers who had previously completed a postgraduate programme in STEAM education were interviewed. The objective is to gather their perceptions and feedback on the strengths and areas for improvement within their experience, particularly concerning STEAM outdoor education.

Methodology

Data was collected through a semi-structured interview conducted with seven in-service teachers—one each from Biology, Physics, Mathematics, and ICT, plus three from primary school—who attended the Outdoor STEAM Education module as part of the Postgraduate Programme in STEAM Education at the Santarém Polytechnic University during the 2023–2024 academic year.

A thematic analysis was conducted on the qualitative data set. In particular, a deductive thematic analysis was undertaken, with the researcher's preconceptions and ideas, developed through the literature review, informing the coding process. The interview protocol was structured around three primary dimensions: (1) participants' perceptions of pedagogical outdoor space utilization; (2) their experiences and outputs from the postgraduate programme; and (3) the translation of acquired skills and knowledge into classroom practices. Nevertheless, any codes or themes that were not aligned with the preconceived concepts were employed to guarantee that the data collection process was adaptable to the teacher's voice.

The Braun and Clarke (2006) six-phase framework was employed for thematic analysis. In the initial stages of data analysis, transcripts were produced from the interviews. The coding process was conducted in a systematic manner, with the transcripts being highlighted and assigned their initial codes. Subsequently, the data were categorized based on their collective meaning. The coded data were then rearranged into more refined themes. Subsequently, the resulting themes were subjected to a process of reflection and review by two researchers, with the objective of ensuring accuracy and relevance.

Findings

The interviews cover professional background, motivations for enrolling in the STEAM Education postgraduate programme, experiences during training (curriculum structure, methodologies, delivery mode), contributions of the STEAM Outdoor Education module, examples of implemented activities, school contextual conditions, teacher collaboration, and suggestions for training improvement. Excerpts reveal rich narratives with concrete practice descriptions (e.g., ecotrail, biocube, schoolyard paths, pedagogical gardens, insect hotels, local pedestrian routes) and reflections on impacts for students, teachers, schools, and communities.

The presentation of results is organized according to the eight themes derived from the thematic analysis of the interviews, following Braun and Clarke's (2006) six-phase framework.

Professional identity building around STEAM Outdoor. This theme captures how in-service teachers from diverse backgrounds (e.g., primary, languages, sciences, ICT) view the postgraduate as a pivotal affirmation of their innovative identities, validating prior paths in active/digital methodologies while fuelling further development like master's pursuits. Participants describe it as "pedagogical path validation" and "right path confirmation," bridging autodidactic experiences (e.g., robotics, field trips) with structured STEAM expertise, fostering confidence to lead as change agents in schools.

Training Quality. Participants overwhelmingly portray the postgraduate programme as offering a well-structured, coherent curriculum with a strong practical emphasis, grounded in active methodologies and, in particular, in STEAM outdoors's hands-on field trips and effective theory-practice integration, which many describe as transformative. This excerpt demonstrates this positive perception of training in the words of one of the participants:

> We diversified learning spaces, and I learned that in this postgraduate programme too. (...) We created outdoor learning scenarios ourselves, meaning we didn't just talk about academic terms in the classroom, we actually went on field trips, and I think that part was very important.

Participants highlight peer sharing, contributions from guest experts (e.g., 3D printing), and Saturday face-to-face sessions as key moments for building professional networks and enriching learning. The hybrid format is generally viewed as appropriate and flexible, although participants consistently call for additional in-person, "hands-on" sessions to deepen engagement. Reported weaknesses focus mainly on the Arts component, which some perceive as insufficiently engaging or not well integrated with the varied disciplinary profiles of the participants.

The positive experience of attending this training programme motivated two participants to enroll in a master's degree, as one of them explains: "I liked the training immensely and that's what motivated me to continue and enrol in a master's... The methodology used in the postgraduate was very motivating".

Transformation toward outdoor-integrated practices. It reflects how the training equips in-service teachers with tools to shift from classroom-bound to outdoor-integrated STEAM practices, enabling them to confidently design and implement authentic activities such as ecotrails (using Actionbound® with QR codes), biocubes, pedagogical gardens, and insect hotels within schoolyards. This training fosters essential sequencing skills, constraint anticipation, and interdisciplinary adaptation across diverse contexts and subjects—including languages—transforming participants who were novices in outdoor structuring into assured implementers who readily share resources and lead collaborative projects within their schools. One of the participants demonstrates the confidence and knowledge that this training has given him to change his practices:

> We can also encourage our students to develop activities and learning scenarios in spaces that do not have to be closed classroom spaces. And that was also a bit of a search for that kind of dynamic and also for knowledge in that area, and it made perfect sense to me, because I feel much more confident now, also here, carrying out the activities.

Student Impacts. In-service teachers consider that STEAM outdoor education fosters student autonomy, confidence, motivation, and critical reflection, with eagerly requesting activity repetition, demonstrating "better self-regulation", expanding vocabulary (e.g., in language classes). As one of the participants points out: "Kids are more autonomous, confident... (…) more willing to ask doubts/intervene. They highlight sustained engagement and clear behavioral shifts from passive recipients to active interveners, supported by student productions and assignments, consistently emphasizing outdoor STEAM's effectiveness for real-world relevance and transversal competencies.

Institutional Barriers. Participants highlight key barriers including lack of planning time, self-funded materials, and municipal disparities in outdoor investments. They contrasted supportive leadership with entrenched transmissive school cultures that prioritize immediate academic results over long-term transversal skills development.

> I feel I lack the time allocated by management for these activities. I handle everything during my personal, non-teaching hours, receiving no institutional time investment despite the effort required to manage implementation under real-world conditions. The available time proves insufficient for quality execution on the ground... It's genuinely challenging!

Peer Collaboration versus Resistance. Participants described supportive peer networks—including WhatsApp groups for resource sharing and collaborative teaching within science clubs—coexisting with resistance from fatigued and individualistically oriented colleagues who remained entrenched in established practices and perceived outdoor STEAM initiatives as additional workload without immediate academic returns. They underscored the efficacy of "change agents" who modelled these activities directly in classrooms, facilitating gradual acceptance and highlighting the necessity of patience to effect fundamental shifts in professional mindsets.

Families and Community Role. Families emerge as “ultimate allies”, who enhanced the legitimacy of STEAM outdoor initiatives through the dissemination of student successes at home (e.g., awards, science fairs, international trips), particularly within primary education contexts. Municipal authorities and parish councils facilitated programmatic extensions such as field trips and community projects. This external involvement effectively helped overcome obstacles, sustained teacher motivation, and extended educational impacts beyond the school environment.

Need for Ongoing Professional Support. Post-training support via virtual communities, dedicated laboratories, and regular mentoring sessions—to maintain implementation momentum, address implementation uncertainties, and counteract post-training demotivation, particularly among initially reticent colleagues. One teacher emphasized that: “virtual communities: maintain thread, support network, share experiences, keep focus active.

Overall, the participants have a highly positive evaluation of the postgraduate programme and highlight several key strengths of the programme. The training was regarded as a valuable opportunity for professional development, with participants reporting that it effectively grounded and validated their knowledge, thereby enhancing their innovative teaching practices. The emphasis on hands-on, practical activities, such as field trips and real-world applications, was particularly praised. Collaborative work also emerged as a key strength, with teachers highlighting the value of sharing experiences and strategies with colleagues. The programme successfully demonstrated how to integrate various disciplines, a crucial aspect of STEAM outdoor education. Participants also appreciated the ongoing support from trainers, who were available for follow-up and to address any questions. Ultimately, participants noted a positive impact on students, observing increased confidence, autonomy, and participation during outdoor activities.

Regarding the less successful aspects of the training and the difficulties they experienced, participants highlighted several challenges. Some secondary school in-service teachers felt the content was primarily tailored to primary education, lacking adaptation for different educational levels. Participants also faced difficulties managing the demanding workload, as balancing training with teaching responsibilities proved challenging. Additionally, some were uncertain about independently implementing STEAM Outdoor methodologies. Many students, unfamiliar with group work or outdoor activities, made practical application more difficult. Finally, there was limited exploration of the artistic component within the STEAM framework, which could have been more engaging and integrated across the curriculum.

Participants highlighted several opportunities for improving the programme. They emphasized

the importance of post-training follow-up through mentoring programmes and ongoing sharing groups to support the practical application of the activities. Additionally, they stressed the need for greater institutional involvement, advocating for increased awareness among school boards and local authorities regarding the value of STEAM outdoor education, alongside efforts to secure more logistical and financial support. Teachers also suggested the development of structured materials and guides to aid in preparing and implementing outdoor activities. Furthermore, they recommended adapting the training to better address the needs of secondary education and expanding the integration of other subjects, including art education, to strengthen the STEAM approach.

Several challenges were identified that could hinder the successful implementation of STEAM outdoor methodologies. Participants reported encountering resistance from colleagues and institutions, making it difficult to engage others in adopting these innovative approaches. The demanding workload and bureaucratic tasks were also seen as significant obstacles, as they limited the time available for integrating outdoor activities into teaching practices. Furthermore, not all schools are equipped with the necessary resources, such as appropriate spaces and materials, to support STEAM outdoor education effectively. A traditional focus on academic results, coupled with a reluctance to change established teaching practices, also emerged as a barrier. Additionally, the lack of autonomy to invest in the development of outdoor spaces, particularly in schools dependent on municipal funding, was cited as a further limitation.

Conclusions

Drawing from the findings of this study, we aim to develop a conceptual framework for a training programme specifically focused on the STEAM outdoor educational approach. The results indicate that in-service teachers feel unsupported within their schools and face challenges in engaging their colleagues in the development and implementation of activities, which is consistent with prior studies (Bentsen et al., 2013; van Dijk-Wesselius et al., 2020). Also, in the study by Pitiporntapin et al. (2023), participants emphasized the need for training opportunities that involve collaboration in the development of interdisciplinary activities. Furthermore, it was found that offering a post-graduation in STEAM Education to in-service teachers across all educational levels (from pre-school to secondary school) led to difficulties in adapting content and activities to the specific teaching contexts and interests of each participant.

In response, a partnership is being established with a local school network to enable the participation of a broader range of in-service teachers, fostering a collaborative environment by bringing together educators who work within the same context. Additionally, the focus of the post-graduation programme will be narrowed to target a single educational level, specifically primary school teachers, in order to ensure more contextually relevant content and activities. Efforts will also be made to strengthen the integration of the arts component within the curriculum, further enriching the STEAM approach.

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Secondary Students' Perceptions Of STEM Subjects In Interdisciplinary Education In The Context Of Education For Sustainable Development

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Interdisciplinary STEM education offers the advantage of addressing complex issues such as climate change through the integration of multiple subjects. By merging these subjects, topics and methodologies can be attributed not solely to one subject but often to multiple subjects, such as diagram analysis or problem-solving. It is therefore essential to understand how students perceive each subject in interdisciplinary STEM education to determine whether the working methods and content of each subject can be applied accordingly, and which working methods and content have connections and differences between the subjects. In this way, points of connections and barriers for teachers and science in the learning process can be made visible. This study investigates students' perceptions of interdisciplinary STEM lessons in geography, mathematics, and computer science. Data were collected through an open digital questionnaire distributed to two ninth-grade classes in a secondary school in Hamburg, Germany (n = 45). Qualitative content analysis of the responses revealed that students perceived diagram analysis in both mathematics and geography; that calculation is part of mathematics, computer science and geography; and that students perceived media with particular subjects, for example, maps to geography and the calculator to mathematics.

Keywords: Qualitative research, Secondary education, STEM education

Introduction

Complex societal issues cannot be addressed solely through the knowledge of individual disciplines within Science, Technology, Engineering, and Mathematics (STEM) (Siller, Vorhölter & Just, 2024). As STEM subjects are taught separately in many parts of Germany, it is essential to integrate knowledge and methodologies from various fields in order to address societal problems holistically (Fensham, 2012). Common methods shared by all STEM disciplines, such as modeling and problem-solving, can be examined in conjunction and facilitate the avoidance of overlaps while promoting meaningful connections between the disciplines (Bacon, 2018). The categorization and perception of subjects in interdisciplinary instruction, from the perspective of students, allows educators to gain a clear understanding of students' perception regarding the subjects in STEM education, which can serve as an indicator of educational success. When these perceptions are made visible, points of connection and potential barriers to learning can be identified and addressed (Hopwood, 2007). A common perception that arises in this context is the reduction of mathematics to numbers and calculations, geography to map work and the memorizing cities and rivers, or computer science to just the computer lab (Beck et al., 2024). Such reductive perceptions offer valuable entry points for uncovering advanced learning content among students. By recognizing students' perceptions of the subjects, it is also possible to highlight barriers between pedagogical research and the actual experiences within the classroom.

The aim of this study is to identify students' perceptions of the subjects of geography, mathematics, and computer science within interdisciplinary STEM education in the context of Education for Sustainable Development (ESD).

The central research question is: What are secondary students' perceptions of geography, mathematics, and computer science in interdisciplinary teaching?

Theoretical Framework

Relevance Of Interdisciplinary STEM Education In ESD

In recent years, there has been an increasing focus on integrated approaches in STEM education, as they contribute to improved student learning outcomes (Jong et al., 2020) while simultaneously promoting the essential competencies of the 21st century (Bybee, 2010; Dare et al., 2022). The integrated teaching of STEM subjects is crucial not only for acquiring specific skills but also for development knowledge necessary to solve real-world problems (Siller, Günster & Geiger, 2024). ESD and STEM education share overlapping areas in educational discourse, as both fields address themes such as climate change and utilize interdisciplinary learning methodologies (Smith & Watson, 2019). According to a systematic review by Kellinghusen et al. (2025a), ESD and integrated teaching in geography, mathematics, and other (STEM-related) subjects complement each other particularly well, as both approaches promote interdisciplinary and context-based learning. Consequently, STEM education presents an opportunity to engage with topics articulated within the context of ESD, thereby contributing to the Sustainable Development Goals (Siller, Vorhölter & Just, 2024). This could enable learners to make informed decisions and take an active role in creating a sustainable society (Vorhölter et al., 2025).

Students' Perceptions Of STEM Subjects

In educational research, students' perceptions of subjects are central, as they often differ from those of subject experts and researchers (Lam & Lai, 2003). Although such differences should not be seen simply as inadequacies or misconceptions on the part of the students, they do reflect students' learning experiences and provide insights for improving curriculum and instructional design (Lam & Lai, 2003). Students' perceptions of a subject are additionally shaped by their motivation to learn, their academic performance, and the teacher (Wong et al., 2002).

There are various terms used in the literature to describe the perception of a subject, which are often used synonymously. The most common terms are 'ideas', 'attitudes', 'beliefs', 'conceptions' and 'perceptions' (Lam & Lai 2003). As there is no consensus on the use of the various terms, the authors have opted for the neutral term 'perception' in this study.

Methods

Sample

To address the research question, an open-ended digital questionnaire was administered to two ninth-grade classes in a secondary school in Hamburg, Germany (n = 45). Ninth grade (14/15-year-old students) was chosen because it represents a transition point before upper secondary education, reflecting accumulated experiences from geography, mathematics, and computer science lessons. At the time, computer science was not yet compulsory, meaning some student may not have received instruction in that subject.

Data Collection

Date were collected with a digital questionnaire in early December 2023 as part of the project "Nachhaltig handeln – MINT4all", which translates in English as "Sustainable action – STEM4all"[1]. The questionnaire included various materials, such as worksheets and slides, which were discussed in the interdisciplinary teaching unit focused on sustainable consumption and climate change. A real-world problem was addressed: whether a locally produced apple is more

[1] This research was funded by Bundesministerium für Bildung und Forschung, grant number 16MF1017.

sustainable in terms of greenhouse gas emissions and water than an apple imported from overseas.

After completing the teaching unit, students were asked to explain in writing, which subjects they perceive in the materials and to explain their reasoning in an open response format. Three material examples and corresponding student perceptions are discussed in this paper.

- The first material (M1) consisted of a worksheet designed for students to compare various apple cultivation regions, focusing on climatic zones, climate data, and seasonal calendars.
- In addition, the second material presented a pie chart illustrating the demand for apples in Germany, which required students to conduct an analysis of the data depicted in the diagram.
- Lastly, the third material (M3) comprised another worksheet where students were tasked with representing the storage of an apple in a cold storage facility over the course of the calendar year using the software GeoGebra.

The teaching materials are available in German at Vorhölter et al. (2025).

Data Analysis

The students' responses were analysed using the qualitative content analysis method according to Kuckartz & Rädiker (2023). Two researchers developed a category system describing students' perceptions of the subjects and their justifications within the interdisciplinary instruction, following a deductive-inductive approach. For the formulation of the deductive categories, the German educational curriculum for geography, mathematics, and computer science was selected (Brinda et al., 2008; German Geographical Society, 2014; Kultusministerkonferenz, 2022). This curriculum outlines the knowledge, methods, and competencies that students are expected to possess by the end of their educational journey in the respective subjects. The subjects, along with the associated content, methods, and competencies articulated in the educational curriculum, partially align with the experiences of the students, as educators utilize this framework for their instructional design, thereby influencing students' conceptions of each subject. To ensure inter-rater reliability in the coding process, a consensual coding approach was employed.

Key Results

Depending on the material, students give different reasons for their perception of a subject in interdisciplinary STEM education in the context of ESD. Selected examples are summarized below, reflecting findings reported in Kellinghusen et al. (2025b).

Calculation As Part Of Mathematics, Computer Science, And Geography

For students, calculation is central not only to mathematics and computer science, but also to geography. One student articulates this aptly: "We calculate how many apples we would be missing without the imported apples. The subject's mathematics and geography play a role in this" (M2_student_11). In another quote, both mathematics and computer science are mentioned in relation to calculation: "Math is used by calculating data just like computer science" (M2_student_43).

Analysing Diagrams As An Interdisciplinary Discipline Of Mathematics And Geography

For the students, analysing diagrams is anchored in both mathematics and geography. This is supported by this statement from one student: "We assessed the material by looking at it. I think it belongs a bit to mathematics (...) and a bit to geography" (M2_student_38).

(Digital) Media Assigned To Specific Subjects

The perceptions of subjects among students indicate that certain media can be specifically attributed to particular subjects. In this context, the use of atlases, maps, and climate diagrams plays a central role in geography. An example of the attribution to geography is: "In order to complete the content of the task sheets, we had to work with climate diagrams, tables, and climate maps from the atlas" (M1_student_38). In contrast, calculators can be assigned to mathematics for students: "That was math, because you had to calculate with a calculator. (M1_student_35)" and the digital program GeoGebra are significant for mathematics and computer science: "GeoGebra from the mathematics class (M3_student_24)" and " using GeoGebra [is] also computer science (M3_student_7)".

Discussion

Our key results highlight the students' perceptions of geography, mathematics, and computer science within the context of interdisciplinary teaching. First, students demonstrated a clear understanding that calculation serves as a fundamental element connecting mathematics, computer science, and geography. They articulated that calculations are not only central to mathematics and computer science but also play a significant role in geography. Second, the analysis of diagrams emerged as a crucial interdisciplinary skill that students associate with both mathematics and geography. Third, students' perceptions emphasized the use of different media linked to specific subjects, such as atlases, climate diagrams, and maps for geography; calculators for mathematics; and the online tool GeoGebra for mathematics and computer science. Lam & Lai (2003) confirm that the perception of the subject as limited to media is not incorrect, but it does not capture the complex understanding of the subject by the respective didactics and academics and provides information on how the curriculum and teaching in schools could be improved.

One limitation of the study is that the personality of the teacher, the teaching methods chosen and the subjects taught in the study have an influence on the results (Wong et al., 2002). Additionally, German educational standards shape students' perceptions of each subject; in another country, different standards might yield different results. Despite these limitations, the results suggest that students perceive that the subjects are not lost in integrated STEM teaching, and that connections among the subjects are, to a certain extent, promoted. These findings support the further implementation of integrated STEM education at the secondary level, as certain students recognize the connections among subjects and perceive subject-specific content. Especially in terms of ESD, it is becoming increasingly important that students are able to make these connections between subjects in order to develop sustainable solutions and better understand complex interrelationships.

Conclusion

In summary, this study highlights that students perceive connections and duplications of categories among geography, mathematics, and computer science in interdisciplinary STEM lessons within the context of ESD. By making these perceived connections visible, educators can gain an understanding of how students perceive the subjects of geography, mathematics and computer science in an interdisciplinary STEM teaching context. These findings require educators to further promote these connections within their curricula and ensure that students not only acquire subject-specific knowledge, but also develop necessary skills to collaboratively tackle and solve complex real-world problems.

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Part 7 / Strand 7

Discourse And Argumentation In Science Education

Co-editors: *Andri Christodoulou & Metin Sardag*

Part 7 / Strand 7 Discourse And Argumentation In Science Education

Understanding, supporting, and promoting the use of evidence and argumentation discourse in science education. Includes scientific practices related to knowledge evaluation and communication, supporting the development of critical thinking, discourse analysis, talking and writing science in the classroom, and meaning making in science classrooms.

Sub-themes:

1) Analysis of Argumentation and Student Discourse in Science Education
2) Developing Critical Thinking through Science Argumentation
3) The Role of Talking and Writing in Science Knowledge Construction
4) Tools and Techniques for Enhancing Scientific Discourse
5) Meaning-making in Science Classrooms

Contents

Strand 7: Discourse And Argumentation In Science Education.....577

Sources Of Information And Media In Biology Lessons: Relationships In A First-Grade High School Classroom.....579

Exploring High School Students' Mobilization Of Critical Thinking Skills Through Argumentation About Climate Change.....585

Deep Dive: Evaluating Students' Use Of Toulmin's Argumentation Pattern In Chemistry Classrooms For Constructing Scientific Arguments About Ocean Acidification.....591

Explaining Facts About Electromagnetic Radiation In Podcasts: Students As Science Communicators.....598

Argument Construction System 'Argu-Made 2.0' To Support The Examination Of Evidence And Scientific Judgement Regarding The Bioaccumulation Of Pufferfish Toxins.....609

Gender Differences In Science Groupwork Participation: Exploring Students' Voices Using Automatic Speech Recognition And Social Network Analysis.....615

Unpacking Science Teachers' Discursive Practices In Instructional Modelling.....624

ESERA 2025 Copenhagen

Strand 7: Discourse And Argumentation In Science Education

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Argumentation and discourse studies in science education can be defined as a broad research field that focuses on how individuals evaluate, justify, explain, discuss, and meaningfully use knowledge in scientific and social contexts on the basis of evidence (Kelly, Brown & Jiménez-Aleixandre, 2023). This field examines how scientific knowledge is spoken about, written, represented, defended, and questioned. Therefore, research on argumentation and discourse constitutes a strong area of intersection among scientific literacy, critical thinking, media literacy, science communication, and socio-scientific issues.

One of the main reasons why this field has become more visible today is that information circulates through media and digital environments at an irresistible speed and reaches large audiences within a short period of time. Misinformation, distorted scientific claims, sources of uncertain reliability, and anti-science discourses spreading through social media make it necessary to question the source of information, its evidence base, the context in which it is produced, and the way it is presented (Osborne & Pimentel, 2023).

The studies included in this section make this need visible through different age groups, subject areas, and methodological approaches. Kelles et al. (2026) examine students' relationships with media content and information sources in biology lessons and reveal the importance of teacher questions in questioning the origin, reliability, and possible conflicts of interest of sources. Matsuyama et al. (2026), through the Argu-made 2.0 system developed in the context of the bioaccumulation of pufferfish toxins, support sixth-grade students' processes of selecting appropriate evidence and constructing claim-evidence-reasoning structures. Dachauer and Lembens (2026) demonstrate that the Toulmin Argumentation Model can be used to improve the structural quality of high school students' scientific arguments in the context of ocean acidification. Santos Coutinho and Sasseron (2026), in a writing activity on climate change using the En-ROADS Climate Solutions simulator, show that students partially activated their critical thinking skills; however, they also needed further pedagogical support for strong justification and the evaluation of alternative perspectives. These studies indicate that selecting evidence, constructing reasoning, and questioning the reliability of information are learning processes that need to be explicitly designed and taught in science lessons.

The discourse dimension of the section includes studies on how teacher-student interactions shape learning opportunities. Cortés Morales and Marzabal (2026) analyse teachers' discursive moves in modeling-oriented instruction that make students' ideas visible, prompt them to question these ideas, and guide them toward a shared scientific model. Loidl et al. (2026), by positioning students who produce podcasts on electromagnetic radiation as science communicators, emphasize that content knowledge alone is not sufficient for producing high-quality explanations; explanation and communication skills also need to be explicitly supported. Kang and Adofo (2026), by combining automatic speech recognition and social network analysis, show that participation in science group work should be understood not only in terms of the amount of talk, but also together with variables such as students' relational positions, gender, science identity, and extraversion. Thus, the section addresses discourse both in terms of teachers' moment-to-moment pedagogical decisions and students' practices of explanation, participation, and

meaning-making.

The main trends in these studies appear to concentrate on argumentation, source evaluation, teacher discourse, the production of scientific explanations, learning supported by digital tools, and equitable participation. Another noteworthy trend is that students are positioned as active meaning-makers who construct arguments, write explanations, produce podcasts, use simulators, question sources, and participate in group interactions.

From a methodological perspective, these studies indicate that classroom interactions should be examined not only through outcome indicators but also through process data. Video recordings, students' written products, simulator outputs, podcasts, automatic speech recognition data, and social network structures show that research on argumentation and discourse relies on multilayered, multi-modal data sources. In this way, the field opens up both the effects of pedagogical interventions and students' positioning in classroom interactions to more detailed discussion.

The themes of sustainability and digital developments also strengthen the contemporary importance of this field. Climate change, ocean acidification, global warming news, food safety, and sustainability-themed group work enable students to relate scientific knowledge to social and environmental responsibilities. Digital argumentation systems, simulators, podcasts, automatic speech recognition, and social network analysis both support students' thinking and communication processes and provide researchers with opportunities to examine classroom discourse in a more detailed and scalable way.

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Sources Of Information And Media In Biology Lessons: Relationships In A First-Grade High School Classroom

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In this paper, we present an ethnographic study in which we observed Biology lessons over an academic year in a Brazilian 1st-year High School classroom. Based on video records of the lessons, we select events in which misinformation was a central part of discussions. These events were described in event maps and transcribed into message units. Analyses were guided by notions of reflection/refraction of language (Bakhtin circle) in order to answer two questions: i) For these students, how does the media reflect and/or refract science when disseminating diverse socioscientific issues? ii) How teachers' questions influenced students' evaluation of information sources throughout the year? As results, the students showed two roles that media could assume: as refracting scientific information, by: i) deceiving; ii) hiding; iii) distorting; iv) using retracted research data; v) using outdated information or manipulating news; or as reflecting scientific information, when: i) being used as checking tools; ii) recognizing mistakes and correcting itself. The teacher's questions were relevant in bringing about changes in students' evaluation of information sources throughout the year. His questions challenged arguments based on authority and gave visibility to key aspects of source analysis, such as explaining a source's origin, assessing the credibility of cited sources and considering possible conflicts of interest. These results bring empirical evidence that pedagogical activities articulated with the aim of promoting autonomous and well-informed positioning can generate learning opportunities beyond superficial criticality.

Keywords: Media literacy, Sources of information, Biology lessons.

Context And Relevance To Science Education

In this study we investigate how High School students discursively constructed relationships between science and media over Biology lessons in a public school in Brazil. Allchin (2022) argues that the role of the media is not secondary in science education. Students should have opportunities to understand how science is mediated, how it is communicated to society and what are the science images disseminated for different media.

Such demands are linked to discussions on how post-truth scenarios has affected schooling and, more specifically, science education in the contemporary world (Allchin, Bergstrom & Osborne, 2024). The media (traditional and new media) are one of the main foci of such issues. Traditional media lose support and trust (Chinn; Barzilai & Duncan, 2021), while new media produce echo chambers and increase the dissemination of fake news (Barzilai & Chinn, 2020).

The role of science education in this scenario goes beyond to promote critical thinking for distinguish between what is "true" and "false", to take critical action (Martínez Pena et al., 2024), what is coherent with the "criticality" notion presented by Davies and Barnett (2015). Other discussions have been demanded at school, such as: who invests in misinformation, what are the interests in propagating it, what is behind false information, what mechanisms are linked to beliefs in misinformation, what is the role of sources (e.g., Barzilai & Chinn, 2020). We seek to contribute to these discussions through a perspective of social interactions in the classroom as linguistic processes in which critical thinking can emerge and take action.

Theoretical Framework And Research Questions

People, through discourse, continually negotiate the meanings of texts, events and contexts in the

flow of their social life. In the post-truth era a very large part of critical thinking is evaluating the truth – or at least plausibility – of the premises (Lyons & Ward, 2024) or claims that are spread by social media.

Thus, meanings of certain textual and contextual elements of language can reflect or refract other texts, events and contexts (Bloome et al., 2022). This conception is particularly relevant to our study. When analysing how students relate media and science, it is important to consider that the meanings, interpretations and relationships proposed by them are intrinsically related to how these students reflect and/or refract histories, cultures, references, knowledge, values and norms.

The notions of reflection and refraction used in this paper are based on scholars from the so called Bakhtin circle. Language can be used to reflect or refract aspects of a culture, a context, a history. When language reflects something, it is maintaining certain historical, social and cultural meanings, without changes or questions, that is, it reproduces what is communicated. When language refracts something, in turn, it is being used to modify the original, historical meanings, considered standard for that particular culture, resulting in changes in meanings (Bakhtin, 1981).

To contribute to discussions in science education field, we investigated discursive interactions in a 1st year high school classroom (15-year-old students in Brazil) over the course of an academic year. The following questions guided the study: i) For these students, how does the media reflect and/or refract science when disseminating diverse socioscientific issues? ii) How teachers' questions influenced students' evaluation of information sources throughout the year?

Research Method And Design

The study took place in a public school in a big city in Brazil. Our research team conducted participant observation and recorded written field notes (Spradley, 1980). Data were gathered from videotaped records of Biology lessons and students' artifacts to better understand forms of participation in the classroom (e.g., Castanheira et al., 2001).

We followed a 1st year high school classroom (9 boys and 24 girls) over the course of the academic year in 2021. As a result of the COVID-19 pandemic, the school adopted an emergency remote teaching system, in which teachers used platforms such as Google Classroom® to communicate with the class. For online synchronous lessons, Google Meet® was used.

The lessons were organized in three cycles of activities (Figure 1) in which students participated in scientific inquiry units (e.g., Pedaste et al., 2015) and activities guided by the use of socio-scientific issues (e.g., Sadler, 2009).

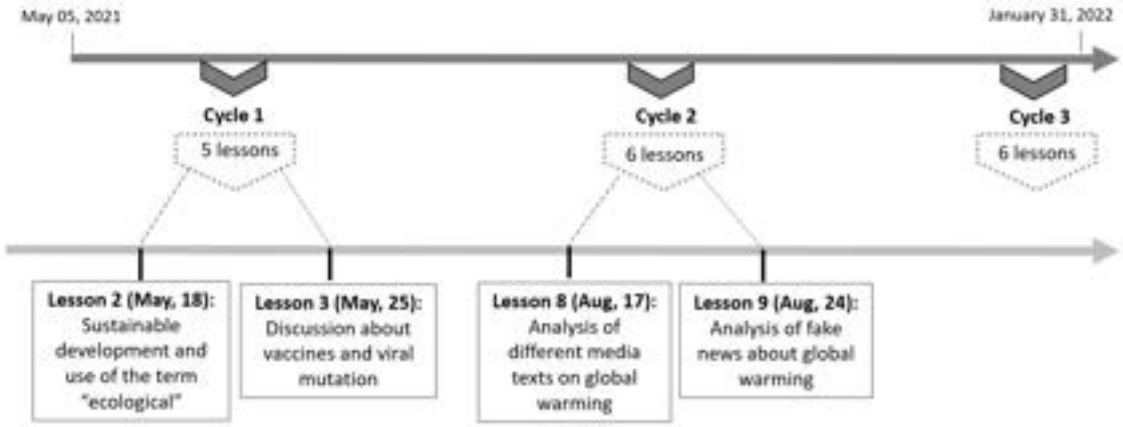
We adopted elements of an ethnographic perspective on education to develop our analysis. We built macroscopic representations, as charts of lessons and event maps (Castanheira et al., 2001) that allowed a broader view of the history of the group in different levels of detail. These representations made it possible to establish whole-part relationships, situating events in the group's history. From this panoramic view, we selected four lessons for analysis of interactions (Figure 1).

When analysing the 17 lessons of the year, we selected 4: lessons 2, 3, 8 and 9. The selected events were chosen because misinformation was a central part of each SSIs discussion in these lessons, thus opportunities for critical evaluation. The events were transcribed word by word and the analysis was guided by proposals on reflection/refraction of language (Bahktin, 1981).

In lesson 2, students analyse three media that use the word "ecological" in different situations: 1) ecological leather for clothing production; 2) water reuse in towel washing; 3) ecological bags produced from organic matter. In lesson 3, the teacher showed a map with the distribution of dengue cases around the world. Then, the students discussed possible relationships between the

development of a dengue vaccine and the ecological data on the map. In lesson 8, students analyse three reposts about global warming. Each repost addressed different aspects of the phenomenon, including false information. Finally, in lesson 9, the teacher showed fake news about global warming that has become common in WhatsApp® groups. The students discussed how they would react to that information if they received it in a group of their families.

Figure 1. Biology lessons selected for analysis in this paper.



Findings

Throughout the selected lessons (Lessons 2, 3, 8 and 9), we identified different relationships between media and science constructed by the students. We also observed changes over the lessons regarding the role of sources. As the complete discursive interactions are too long for this paper, we opted for showing excerpts from the participants' discourse in order to illustrate the analyses (Figure 2).

Regarding our first research question, the analysis indicates different interpretations by students about the relationship between media and science. We found events in which the media was interpreted as an agent capable of refracting scientific information, when it acted by: i) deceiving the reader (Lesson 2 and 9); ii) hiding data (Lessons 8 and 9); iii) distorting them (Lessons 3 and 8); iv) using retracted research data (Lesson 8); v) using outdated information (Lesson 8); or manipulating news (Lessons 2, 8 and 9).

Despite this, the students also indicated the media as an agent capable of reflecting scientific information. For example, when the media: i) consistently uses scientific knowledge (Lessons, 2, 3 and 8); ii) disseminates actions corresponding to scientific practice (Lesson 2); iii) promotes actions aligned with science official discourse (Lesson 2); iv) recognizes mistakes and corrects itself (Lesson 9). In addition, the students indicated that the media could also act in this way by functioning as a tool for checking information (Lessons 2 and 8).

Regarding our second research question, we mapped teacher issues onto student performances when evaluating information sources. Table 1 shows some of these questions.

In the first lessons of the school year, the students started from more restricted analyses, relying on arguments from authority. The teacher's questions challenged authority arguments, which appeared, for example, in the speeches of Gleice and Gisele (Lesson 2). In addition, the questions gave visibility to relevant aspects of source analysis, such as the need to explain the origin of the source and, even, to send them to colleagues, as seen, when discussing with Isabel (Lesson 3). In lessons 8 and 9, we observed more complex verifications that included assessing the credibility of the cited sources and considering possible conflicts of interest (e.g., Gisele's remarks in Lesson 8 and Lúcia's in Lesson 9). Questions made by the teacher were also important in this process.

Figure 2. Illustrative excerpts from the analyses. All excerpts are student speeches over the lessons.

	Lesson 2	Lesson 3	Lesson 8	Lesson 9
How does the media refract scientific information?	"it was a lot of marketing by these companies to put the word ecological" "all three are useless, because it doesn't help those who consume think they are leaving of consuming animal leather since it is not true" "it's more of an excuse to say you did something"	"I confused some data, it's been more than three months that I had been watched"	"in this text, he used the fallacy of authority a lot" "not to mention that the research is from 1958 and his text is from 2017, and notions of global warming have already changed a lot" "in the text itself, he uses very complicated words and graphics to try to somehow fit the research done" "He also uses information in a distorted way to convince people"	"Many of his studies have montages in the images. He makes a mistake and that's why his information was wrong" "Teacher, what you said is true that there is manipulation of the news even from important newspapers" "Of course, this newspaper will stop criticizing climate change. Not necessarily spreading misinformation but choosing what they're going to talk about."
How does the media reflect scientific information?	"there was a survey there in the United States that even made a documentary in which the result was that even if everyone reduced the water bill by forty percent, it would not be enough to not run out of water in the near future why the problem it's the industries" "I logged into the hotel's Instagram while we were discussing and I didn't see anything about tree planting"	"I saw a video from a YouTube channel. It's something like that. They brought the data and then the vast majority of people got dengue haemorrhagic fever. They brought the research data" "I saw reports talking about studies of two new viruses that cause symptoms similar to those of dengue or Zika that were being researched, but it is not yet known if these are dengue virus"		
How do students deal with sources of information?	"it is a biologist who creates, because I think it conveys more credibility" "the last one was the only one that we thought the term ecological fits and also the only one [media] that has the real intention of helping the environment so much so that he was a biologist, right?"	"The information is from a biomedical". "Googling more, I just found an infectologist talking about the 5 dengue viruses".	"NASA only posts on its website, the research it uses as a basis" "The sources he uses are unreliable and he uses this political scope a lot"	"the sources he uses are not very reliable" "he also uses an author a lot in this report. A man called Nils-Axel Mörner, who was a former president of the IPCC. When we went to research, we saw that he is not a source that has credibility"

We identified some challenges over this process. Even in the lessons we observed more complex analysis of sources, students still gave authority to some figures without going into detail (e.g. the authority that Izabel gave to the teacher and the researcher who had written the text analysed in classroom 8). So, the changes in analysing sources of information did not happen linearly but happened throughout the events in a variable way and correlated to teacher's questions over the discussions.

Table 1. Excerpts of the teacher's questions over the lessons and students' reactions.

Lesson	Teacher questions	Student	Excerpts from students' performances in evaluating sources
2 2	So, I wanted to put a reflection here for you to think about. Is there a biologist who does bad things for the environment?	Gleice	(…) the third one is interesting (..) that says is a biologist who creates, because, yes, I think it gives more credibility.
	Does every biologist have this environmental concern because he is a biologist? So, for you to think about (…)	Gisele	Yes, the real intention of helping the environment so much so that he was a biologist, right?
3 3	Based on what are you saying this? On a report you saw in a newspaper?	Izabel	I saw a video from (…) from a YouTube channel (…) they show the data from research.
	Because when we make a statement like that, it's good to bring the source, the data that we are relying on (…) Can you send it to us?	Izabel	Yes, I'll send it (…) I'll send it.
8 8	You commented on partisan political use of information, remember?	Gisele	(…) the text (…) it is radical to one side. The side that does not consider what (…) what the human being affects.
	But you have to doubt and even criticise what I say (…) Got it? You must be critical of your own teacher	Izabel	Wow teacher (…) I said (…) he is making fun of us (…) seriously, he didn't (…) he didn't put this here (…) for real
9	You should check what's in the source, who is that source (…) Who's talking about this?	Lúcia	There is manipulation of news (…) this newspaper not necessarily (…) will spread misinformation but choose what they will say.

Conclusions

The results of this research bring empirical evidence that pedagogical activities articulated with the aim of promoting autonomous and well-informed positioning can generate learning opportunities beyond a shallow criticality. We align ourselves with the proposals of Barzilai and Chinn (2020), when they suggest that science education should go beyond just identifying deficiencies in people's knowledge and skills to critically deal with information. Science teaching must be able to deal with cognitive biases, assessing disagreements about "how to know", recognizing and coordinating multiple epistemologies.

The analyses indicate challenges in this process. Naive views about science and difficulties in engaging in argumentative practices are examples of such challenges (Nehring, 2020) and were identified in our data. In this context, the teacher has a role in the organization and conduction of didactic processes. Our analyses reinforce the importance of the school as a fundamental institution in social organization, as well as the need to value actions and curricula for autonomous and critical students.

Acknowledgement

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Exploring High School Students' Mobilization Of Critical Thinking Skills Through Argumentation About Climate Change

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The purpose of this study was to investigate how Brazilian high school students mobilized critical thinking through a writing activity in the Chemistry class in which the students had to investigate and analyse a simulator related to the impact of anthropogenic variables on climate change, entitled En-ROADS Climate Solutions Simulator. The activity was developed with 57 first-year high school students at a Brazilian public school in the state of São Paulo. In order to analyse the information collected, we used the Critical Thinking Analytic Rubric (CTAR), composed of 6 categories (interpretation, analysis, evaluation, inference, explanation and disposition) evaluated with scores from 1 to 6. The results showed that students mobilized half of what would be expected to be the ideal level of high cognitive demand skills related to critical thinking, since most of the scores were at the midway point. This highlights the need to promote more activities in science teaching that help students develop critical thinking, but it also reveals limitations both in the wording of the activity questions analysed in this study and in the ability of the rubrics to assess actions related to critical thinking. Therefore, it is interesting that further research on the topic is conducted in order to address these issues.

Keywords: Critical Thinking. Scientific Argumentation. Classroom Research.

Introduction

In recent years, the spread of misinformation and disinformation involving scientific topics through digital means has reached alarming proportions and, even though young people are usually expected to have skills necessary to use today's technology effectively, studies show their struggle with evaluating information (Osborne et al., 2022). Considering this, it is a Science Education priority to promote classroom research and practices that foster students' higher order thinking skills development by understanding the social practices of science, evaluating information, and developing a consensus that help justify trust in scientific knowledge.

Therefore, critical thinking (CT) development, which is associated with higher order thinking skills such as the ones described above (Saxton et al., 2012), is essential to promote the development of critical subjects who can identify incorrect scientific information, hopefully reducing its spread. Based on that, this study's objective is to answer the following research question: "*How do high school students mobilize critical thinking skills in the Chemistry class through a writing activity aligned with a global climate simulator analysis?*"

Conceptual Rationale

The development of CT is considered a consensual objective of education by scholars (Jiménez-Aleixandre & Puig, 2022; Kuhn, 1999; Kuhn, 2019). Despite this, its understanding and definition are not homogeneously disseminated, that is, there are different perspectives regarding the characterization of CT, involving its meaning, components and how to develop them (Jiménez-Aleixandre & Puig, 2022).

One of the first and most influential definitions was proposed by Ennis (1985), who defined CT as "reasonable, reflective thinking that is focused on deciding what to believe and do" (p. 45). Later, the American Philosophical Association (APA) held a Delphi panel with various CT

experts, including Ennis, aiming to propose a consensual definition of CT. This panel considered that CT include both cognitive and dispositional dimensions, defining it as "purposeful, self-regulatory judgment which results in interpretation, analysis, evaluation, and inference, as well as explanation of the evidential, conceptual, methodological, criteriological, or contextual considerations upon which that judgment is based" (Facione, 1990, p. 2).

Years later, Davies and Barnett (2015) discussed some shortcomings of the APA definition, such as its rooting in only one kind of CT, related to argumentation and judgment formation. For this reason, they proposed changing this perspective to one in which CT consisted of "criticality," a perspective including action. Even though both movements considered that the development of skills and dispositions related to CT are important, the criticality movement differed from the traditional CT movement because it defended that the skills and dispositions by themselves weren't enough and they should be guided by ethical values and result in critical action.

Similarly, Jiménez-Aleixandre and Puig (2022) reviewed and proposed a holistic characterization of CT aiming to explicitly integrate both perspectives. This proposal considers that CT is characterized by two sets each one comprised of two components, the first set marked by purposeful judgment, aligned with the APA definition, with the components cognitive and epistemic skills and critical character; and the other set marked by civic participation and social justice, aligned with criticality, with the components independent opinion and critical action.

Regarding CT assessment, it is commonly derived from multiple choice tests, such as Critical Thinking Assessment Test (CAT) (Stein & Haynes, 2011) and Watson-Glaser Critical Thinking Appraisal (Watson & Glaser, 1964), which arguably do not measure the higher order skills associated with CT, since they are not designed nor have the purpose of formative feedback (Reynders et al., 2020; Saxton et al., 2012). Given this, instead of using tests to assess CT, rubrics could be used, as they provide more detail regarding the scores, what is being measured and what should be included in the data interpretation (Saxton et al., 2012).

Considering this, Saxton et al. (2012) proposed and experimentally studied the Critical Thinking Analytic Rubric (CTAR), heavily influenced by the APA definition, stating that it can be used by raters to score student work samples in a consistent manner. Since they adopted the APA definition as the construct for the instrument, it focuses on the cognitive and epistemic skills and critical character, assessing "five cognitive skills (interpretation, analysis, evaluation, inference, and explanation) and the disposition towards thinking critically" (Saxton et al., 2012, p. 254), rating these categories in scores of 1 to 6.

The categories are briefly defined as follows: *Interpretation* is concerned with understanding and accurately communicating the meaning of information; *Analysis* involves examining and comparing different sources of information; *Evaluation* involves identifying arguments and judging the credibility of sources; *Inference* involves making realistic predictions and forming rational and logical conclusions; *Explanation* is related to the use of evidence and reasoning to support an argument or perspective; *Disposition* towards CT is an affective dimension of CT, highlighting the need for the person to be motivated to mobilize their higher order thinking skills (Saxton et al., 2012).

Methodology And Research Design

This study uses a qualitative approach (Erickson, 2012) and involves the analysis of an activity carried out at a public school in São Paulo (Brazil) in the Chemistry subject by 57 first year high school students (14–16 years old) from different social classes and ethnicities in two classes, divided in 6 groups of up to 5 students per class, totaling 12 groups, anonymized as G1 to G12. The students received tablet computers with internet connection and they had to answer a question

while exploring the En-ROADS Climate Solutions Simulator (Climate Interactive & MIT Sloan, 2023), which is a simulation model that allows the exploration of scenarios focused on how changes in taxes, subsidies, carbon prices, and other factors can alter global carbon emissions and the global temperature in the following years. After the activity was completed, we collected the written responses and digitized them following the ethical procedures of informed consent, transparency and confidentiality.

We provided the students with a worksheet that introduced the simulator, explaining it was developed by Climate Interactive and the MIT Sloan Sustainability Initiative. The worksheet also had a summary of a special report of the Intergovernmental Panel on Climate Change (IPCC, 2022) that stated the goal of limiting global warming to around 1.5°C (2.7°F) by 2100. The question was as follows: "*Point out two variables present in the En-ROADS Climate Solutions simulator that you consider most important to be changed to achieve the target proposed by the IPCC. Explain how changing these variables can influence global temperature.*"

In order to analyse the students' responses, we used the CTAR instrument (Saxton et al., 2012) adapted to the question the students had to answer, as presented in Table 1. Both authors scored the responses individually and then compared the scores, discussing and reaching consensus regarding the divergent scores.

Table 1. Overview of the Critical Thinking Analytic Rubric. Adapted from Saxton, Belanger and Becker (2012).

Rubric categories	Scores					
	1	2	3	4	5	6
Interpretation	Demonstrates no ability to work with the key concepts	Demonstrates an extremely limited ability to work with the key concepts	Demonstrates an uneven or shaky ability to work with the key concepts	Demonstrates a clear ability to work with the key concepts	Demonstrates a strong ability to work with the key concepts	Demonstrates confident ability to work with the key concepts and terminology
Analysis	Does not identify patterns in the evidence	Incorrectly identifies patterns in the evidence	Superficially identifies patterns in the evidence	Identifies patterns in the evidence	Accurately identifies patterns in the evidence	Accurately identifies important patterns in the evidence
Evaluation	Ignores all alternative perspectives	Ignores obvious alternative perspectives	Superficially evaluates obvious alternative perspectives	Evaluates all alternative perspectives	Evaluates most perspectives	Thoughtfully evaluates all perspectives

(Table Continues)

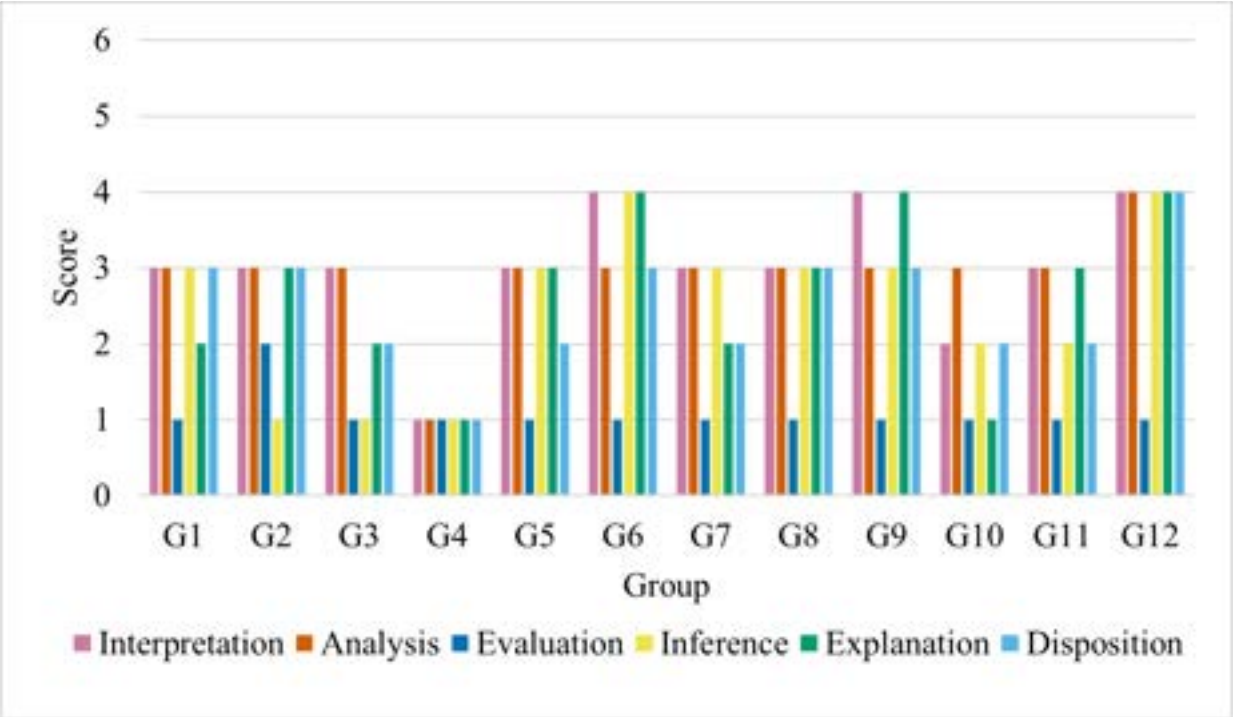
Table 1. Continued.

Rubric categories	Scores					
	1	2	3	4	5	6
Inference	Cannot extend key concepts or make predictions	Inadequately extends key concepts or make predictions	Shakely extends key concepts or predictions	Adequately extends key concepts	Clearly extends key concepts to make predictions	Confidently extends key concepts to make predictions and analyse implications
Explanation	Uses fallacious or irrelevant reasons	Conclusions lack support	Conclusions are weakly supported	Conclusions appear reasonable through use of support	Strong, warranted conclusions	Judicious, persuasive conclusions
Disposition	Close-minded, hostile to reason	Defends only with a single perspective, ignores others	Follows evidence but ignores context	Fair-mindedly follows evidence, addresses context	Fair-mindedly follows evidence, considering context	Objectively considers context and evidence

Findings

The results of the CTAR scores for the response of each group can be seen in Figure 1.

Figure 1. CTAR scores' results for the students' responses.



Although we analysed all the responses, for the purposes of this study, we present, as examples, the analysis of G10's and G12's responses. They presented, for the most part, the lowest and highest scores, respectively, among those with at least *Disposition* score 2, considering that a *Disposition* score 1 means that the response didn't present any justification, which was the situation of G4, whose response only pointed out the variables but did not justify the choice. It is important to note that the student's responses were written in Portuguese and were translated to English for this paper.

G10's response was as follows: "*The increase in the carbon price and the decrease in methane gas emissions. With the increase in the carbon price, we would use less forms and objects that emit gas, and the decrease in methane gas emissions increases the greenhouse effect on Earth.*"

Regarding *Interpretation*, G10's response showed a limited ability to work with the key concepts, considering that they stated that the decrease in methane gas increases the greenhouse effect when it's the opposite, hence score 2. As for *Analysis*, both variables listed were related to the decrease of the global temperature, but this relation is presented superficially, therefore score 3. In regard to the *Evaluation* category, the response did not present any alternative perspective, so score 1. Considering *Inference*, as they incorrectly relate the methane to the greenhouse effect and don't provide much detail about the increase in the carbon price, the category's score was 1. In the matter of the *Explanation* category, the reasons used to warrant the claim are incorrect, hence score 1. Finally, as regards the *Disposition* category, the response only defended one perspective and didn't discuss the context that prevents those variables from being changed, so score 2.

G12's response was as follows: "*The main variables that need to be changed to limit the temperature to 1.5°C by 2100 are: coal, the oil market, and the carbon price, as these are issues that directly impact climate change. Another variable would be the economic development of Third World countries that would reduce the burning of fossil fuels as an energy source and replace it with the use of clean and renewable energy.*"

From this response, we realized that, in relation to *Interpretation*, G12 not only identified both variables, but also perceived the nuance of the relation between the economic situation of a country and its access to sustainable energy, therefore, score 4. Regarding *Analysis*, they identified correctly the patterns in the evidence, thus score 4. As for *Evaluation*, we noticed that they only explained the positive sides of changing each variable, ignoring other points of view and hurdles needed to be overcome in order to change those variables, therefore, score 1. Since they adequately extended the key concepts, especially the relation between economic development and renewable energy sources, *Inference*'s score was 4. Furthermore, as they did not raise any negative side, *Explanation* seems reasonable rather than fully justified, hence score 4. Finally, regarding *Disposition*, we considered that G12 followed the evidence provided by the simulation and addressed the socioeconomic context, therefore, score 4.

Conclusion

In this study, we sought to investigate how high school students mobilize CT skills by structuring their arguments after analysing anthropogenic variables that contribute to the worsening of climate change with the help of an online simulator. Through the data presented, we noticed that most of the categories presented scores equal to 3, stating that in general the students mobilized half of what would be expected to be high cognitive demand skills related to CT.

Interpretation was the skill they managed to mobilize the best, considering most of the groups, except for G4, achieved a score of 3 or higher. This is evidence that the students, in the context of the Chemistry class, are more comfortable with working and applying the key concepts related to the subject.

The poor result in the *Evaluation* category may come from the wording of the question, which did not explicitly ask for alternative points of view. The only group that achieved a score higher than 1 was G2, that pointed out the variable of nuclear energy and briefly talked about its risks, while defending it to be clean and safe due to containment systems.

In future research, we should create the questions considering the opportunity to talk about different perspectives so that the students can better mobilize the *Evaluation* category. The new

questions should be created in a way that the students are motivated to mobilize high cognitive demand skills, so that the questions can't be answered with low score mobilizations.

The CTAR, as previously mentioned, is heavily tied to the APA definition of CT (Facione, 1990). So, it doesn't assess critical action and critical virtue defended by the criticality movement (Davies & Barnett, 2015). Considering this, it is important to state that only assessing students' essays and activity responses does not provide the full picture of CT mobilization, as it can be mobilized through actions and dialogue (Jiménez-Aleixandre & Puig, 2022; Kuhn, 2019).

Finally, this study's findings indicate both the urgency of implementing practices that mobilize CT in Science classes, since students don't seem to be used to mobilizing all the CT skills, as well as the need for academic research in Science Education regarding CT development, such as the assessment of students' criticality, as rubrics are limited to assess actions.

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Deep Dive: Evaluating Students' Use Of Toulmin's Argumentation Pattern In Chemistry Classrooms For Constructing Scientific Arguments About Ocean Acidification

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Science education plays a key role in helping students to become responsible citizens, capable of making appropriate decisions based on scientific information, participating in discussions on socio-scientific issues (SSIs), and taking action in the context of climate change. Thus, achieving scientific literacy in general and practising scientific argumentation skills – as part of scientific literacy – in particular, are essential. Therefore, the pilot study presented here focusses on improving upper secondary students' (ISCED 3) scientific argumentation skills by implementing Toulmin's Argumentation Pattern (TAP) in the chemistry classroom. We focus on chemistry education to better understand subject-specific argumentation in chemistry classrooms. This pilot study is part of an interventional study that aims to implement TAP as a construction mechanism to improve students' scientific argumentation skills. Our study is embedded in the SSI of human-induced ocean acidification. In order to gain insight into students' scientific argumentation patterns and develop adequate teaching materials, we asked 29 upper secondary students to write well-founded arguments to confirm a claim about calcification of coral skeletons made in a newspaper headline. Students' arguments were constructed prior to and following the provision of support material based on TAP. These arguments were analysed with regards to their formal quality using qualitative content analysis. Our findings indicate that TAP aligned well with our participants' intuitive arguments. We discuss our findings and propose how using TAP can contribute to teaching and learning chemistry-specific argumentation skills.

Keywords: Scientific Argumentation, Scientific Literacy, Classroom Research

The Need To Improve Scientific Argumentation Skills In Chemistry Education

At present, society is confronted with numerous challenges regarding climate change (IPCC, 2023). To address these challenges, science education plays a key role in helping students to become responsible citizens, capable of taking action in order to protect our environment (Bianchi et al., 2022). In this context, there is a relevant association with scientific literacy as "the ability to engage with science-related issues, and with the ideas of science as a reflective citizen" (OECD, 2019, p. 100). Being scientifically literate is fundamentally tied to using scientific information, i.e., to making appropriate decisions and participating in public discussions about socio-scientific issues (SSIs) (Lederman et al., 2024). Subsequently, on the one hand, students should be able to re-construct already existing scientific arguments and, on the other hand, construct their own ones (Cavagnetto, 2010; Christodoulou & Grace, 2019; Osborne, 2002). At the same time, students' lack of scientific literacy in general (Lederman et al., 2024), and argumentation skills in particular (Osborne, 2002), is problematic. Osborne and colleagues (2016) demonstrate the validity of an overarching instrument for assessing argumentation skills. We adopt one of their major implications here, proposing that "[e]xercises that asked students to distinguish claims, warrants and data would provide a foundation for more demanding exercises which asked students to construct their own arguments" (p. 841). As Toulmin (2003) distinguishes between claims, warrants and data explicitly, we use Toulmin's Argumentation Pattern (TAP) in this study to understand upper secondary students' (ISCED 3) intuitive scientific argumentation in the chemistry classroom.

TAP In Chemistry Education

Following Toulmin (2003), arguments follow a structure based on up to six elements: data, warrants, backing of warrants, modal qualifiers, rebuttals, and the claim itself. TAP is widely used (Henderson et al., 2018) and has proved suitable for analysis of scientific arguments (Erduran et al., 2004; Lieber & Graulich, 2022). Although the idea of implementing TAP (e.g. Erduran et al., 2004; Lazarou & Erduran, 2021) or an adapted version (e.g. McNeill et al., 2006) in the classroom is not new in science education, studies are required that help to delineate a chemistry-specific approach at the secondary level (Christodoulou & Grace, 2019).

Above and beyond subject matters, SSIs are excellent vehicles to practise scientific argumentation (Christodoulou & Grace, 2019). Tackling SSIs via argumentation enables students to become responsible citizens capable of facing global challenges (Sadler, 2004). Argumentation, in terms of formally connecting premises to conclusions, is generisable. Yet, making an argument within SSIs requires domain-specific knowledge (Tricot, 2018). Therefore, our study uses the chemical side of human-induced ocean acidification, which is highly relevant when discussing climate change (IPCC, 2023).

Research Question

This contribution gives insights into a pilot study that poses the following research question, focussing on upper secondary students in chemistry education: How can the implicit implementation of TAP in a chemistry lesson support students in applying this pattern to improve the structural quality of their scientific arguments? In this case, ‘implicit’ refers to the introduction of TAP elements through scaffolds without explicitly naming or defining these elements, allowing students to engage with them intuitively.

Research Method And Design

The present study was designed as a pilot study that aimed to evaluate whether implementing TAP in the chemistry classroom can improve students’ scientific argumentation skills in the context of human-induced ocean acidification. Prior to an actual intervention, we evaluated how students re-constructed preset scientific arguments. 29 students with prior declarative knowledge about human-induced ocean acidification from 11th and 12th grade from a general high school in Austria participated in this study, taking place in a 50-minutes chemistry lesson. At first, a picture of a fictional newspaper headline claiming ‘calcification of coral skeletons is impaired’ was presented to the students.

Phase I: Students were first asked to individually formulate a well-founded written argument supporting the headline, based on their current knowledge about human-induced ocean acidification from the perspective of a climate activist.

Phase II: Afterwards, students were prepared with ‘argumentation cards’. These cards contained part of an argument, each corresponding to an element (e.g. data, warrants) of TAP, and enabled various thematic lines of reasoning (e.g., lime-carbonic acid cycle, pH, solubility of calcium carbonate in solutions of varying pH, solubility of carbon dioxide gas in water). Technically, these cards could be used to form up to seven different arguments to confirm the claim. Cards corresponding to the same element were coloured the same, helping students to recognise patterns between these elements. Apart from this structuring aid, no further information about these elements was given to students. The sole instruction provided to students was that the utilisation of these cards could be in any combination deemed suitable, including the use of more than one card of the same colour, or omitting the entire cards of one colour. In this phase, students worked in pairs discussing which cards were suitable to support their claim but did not formulate a written

argument.

Phase III: Subsequently, students individually composed another written argument – this time using the previously selected argumentation cards – to support the headline regarding the impairment of coral skeletons calcification.

Phase IV: In a final phase, students were asked to formulate an additional written argument without any support materials, analogous to Phase I. However, due to time constraints, only a few students reached this phase.

Throughout all phases, students were provided with additional supporting material containing information about basic chemical concepts (e.g. chemical equilibrium, pH) relevant in this context. We chose this strategy to even out individual variance due to prior knowledge, allowing the students to focus on the argumentation process itself.

Analysis And Findings

Students' written arguments from phases I, III and IV were analysed regarding their structural quality through structural qualitative content analysis (Mayring, 2022). Content accuracy was not addressed in this contribution, as it was evaluated in a separate study (Dachauer & Lembens, in press). For the structural analysis, a deductive category system initially based on TAP was used. Due to challenges in assigning sequences of students' arguments to the categories *warrants* or *backing of warrants*, which required intense communicative validation (Steinke, 2004) between the raters - and even then, in some cases more than one categorisation would have been applicable – these two categories were merged into a single one labelled reasoning. This approach aligns with McNeill et al. (2006). As rebuttals were neither incorporated into the construction of the support materials nor observed in students' arguments, they were not included in the category system underlying the structural analysis. Based on the analysis of students' arguments and existing literature (McNeill et al., 2006; Toulmin, 2003), the coding system was further developed and serves as the foundation for a deductive coding approach in the planned follow-up study. This category systems comprises the following categories and their respective definitions:

- *Claim* refers to the statement whose content must be demonstrated and whose validity must be determined.
- *Data* refers to data and/or facts that serve as the basis for the argument and supports the claim.
- *Reasoning* refers to justifications, explanations, or elaborations that provide a basis for the claim in relation to the data. 'Reasoning' functions as a kind of bridge between the claim and the data. It can also reinforce the claim.
- The *Modal qualifier* provides information about the degree of certainty or binding force of the reasoning used to support the confirmation of the claim.
- *Other* refers to a sequence that cannot be assigned to any of the established categories.

During the process of assessing intercoder reliability, distinguishing between *data* and *reasoning* was occasionally challenging. This was due to the fact that some sequences were introduced with linking words such as *due to* or *because*, which could give the impression of aligning with *reasoning*. However, detailed content analysis revealed that these sequences often served as the foundation of an argument and should therefore be categorised as *data*. Two examples are given in Figure 1. Both examples demonstrate that the underlined linking words can introduce either *reasoning* or *data*, depending on the specific content they accompany.

During the communicative validation process between the two raters (Steinke, 2004), aimed at better defining and distinguishing between *data* and *reasoning*, the concept of the *'conceptual*

bridge' emerged as a visual representation to illustrate the connection between *claim*, *data* and *reasoning*.

Figure 1. Distinction between data and reasoning in students' arguments (students' arguments from phase I, Pos. 5-6 and phase III, Pos. 78, translated from German).

The calcification of coral skeletons is impaired because, due to the intense exchange of CO_2 caused, for example, by the combustion of fossil fuels, carbon dioxide dissolves in seawater and reacts to carbonic acid. From this hydrogencarbonate and oxonium ions are produced in the water. Due to the increased concentration of H_3O^+ ions, the pH of the seawater increases. Although the pH remains in the basic range, it nevertheless harms the calcification of coral skeletons.

Because the pH in the ocean decreases and the CO_2 concentration in the water increases, the calcification of coral skeletons is impaired. This occurs because coral skeletons require solid $CaCO_3$ to form lime, and the decrease in pH increases the solubility of solid $CaCO_3$ in water.

Legend: data – reasoning

This *conceptual bridge* breaks down students' arguments into distinct components, focusing exclusively on *data*, *reasoning* and *claim*, while disregarding *modal qualifiers* and the category *other*. The student argument presented in Figure 2 serves as an example to illustrate the concept of the *conceptual bridge* in Figure 3. As demonstrated in Figure 2, the student's argument includes more than just the elements *data*, *reasoning* and *claim* – in this case, it also contains a modal qualifier. However, this modal qualifier is not relevant to the conceptual bridge.

Figure 2. Example of a student argument (Student argument from Phase III, Pos. 3-4, translated from German).

The pH decreases, as a result, it is certain that the calcification of coral skeletons is hindered. Coral skeletons require solid $CaCO_3$, but the decrease in pH increases the solubility of solid $CaCO_3$ in sea water, which leads to less solid $CaCO_3$.

Legend: data – modal qualifier – claim - reasoning

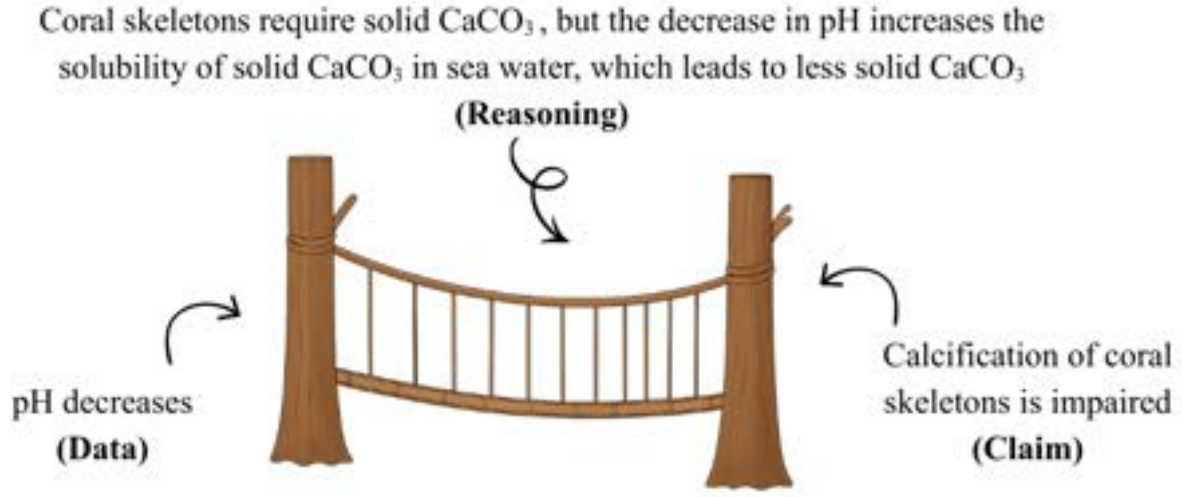
In order to determine whether a sequence of a student's argument serves as either *data*, *reasoning* or *claim*, the *conceptual bridge* can be used as a tool for discussion between raters. Furthermore, it may also serve as an instructional instrument to help students actively distinguish between these elements in their own arguments. As illustrated in Figure 3, *data* and *claim* are visualised as bridge pillars, literally forming the foundation of the bridge – and, figuratively speaking, the foundation of the argument. *Reasoning* functions as the bridge itself, connecting the two pillars and enabling movement from one to the other. This visualisation emphasises the essential link between *claim* and *data* within the structure of scientific argumentation.

A total of three iterative coding cycles took place, each followed by communicative validation between the two raters. Table 1 illustrates the development of intercoder reliability across these three coding cycles.

To assess intercoder reliability, we began by coding students' arguments from phases III and IV – written after the intervention – under the assumption that these arguments would be easier to categorise. We used them to refine the definitions of each category and to add anchor examples to the coding system. Consequently, the category *other* did not exist during the first coding cycle for students' arguments in phases III and IV. This category was introduced during the first communicative validation and is therefore not referenced in the coding of students' arguments

from phases III and IV coded in the first cycle.

Figure 3. Conceptual Bridge (Students' arguments from Phase III, Pos. 3-4, translated from German; Bridge generated with ChatGPT).



In addition, intercoder reliability increased significantly across all coding cycles of phase III. Between the first and second cycle, the visualisation of the *conceptual bridge* was created and initially discussed between the two raters. Between the second and third cycle, this visualisation was incorporated into the coding system, along with an anchor example. However, assessing intercoder reliability for students' arguments of phase I remained challenging, even with the visualisation of the *conceptual bridge*. During this process, intense communicative validation took place between the two raters, with each arguing for their own coding strategy, using the *conceptual bridge* visualisation. No agreement on coding modal qualifiers was reached during the first coding cycle of students' arguments of phase I. This can be attributed to the absence of relevant anchor examples needed to define this category. While one rater coded sequences such as *so*, *decisive* or *therefore*, the other only coded sequences only where the degree of certainty was explicitly stated, such as *therefore, it follows with certainty* or *presumably follows*. Consequently, more diverse anchor examples were added to the coding system, resulting in higher reliability in the subsequent coding cycles. Also, intercoder reliability increased significantly between the first and the second coding cycle of phase I, whereas this was not the case during the final intercoder cycle.

Table 1. Development of the intercoder reliability over three iterative cycles.

		Claim	Data	Reasoning	Modal qualifier	Other	κ
Phase I	1st	38.46 %	47.06 %	34.78 %	0 %	22.22 %	**0.22**
	2nd	83.64 %	90.57 %	67.61 %	68.97 %	100 %	**0.74**
	3rd	91.23 %	96.30 %	73.24 %	91.43 %	100 %	**0.84**
Phase III &	1st	89.66 %	45.71 %	23.33 %	66.67 %	-	**0.43**
	2nd	92.96 %	78.87 %	78.26 %	88.89 %	0 %	**0.80**
	3rd	98.59 %	91.43 %	82.86 %	98.18 %	100 %	**0.91**
Total		**95.31 %**	**93.55 %**	**78.01 %**	**95.56 %**	**100 %**	**0.88**

Our analysis of students' approaches to structuring their arguments revealed a broad use of TAP across all phases. However, the significance of these elements was generally low in students' arguments from phase I. While modal qualifiers appeared in all phases, their use became more nuanced after the intervention – for example, shifting from phrases like *so* or *this leads to* to *this*

probably leads to or *this could lead to*. This enhancement is likely attributable to the provision of the pre-structured argumentation cards. Furthermore, the different elements in students' arguments were not seamlessly linked during phase I. After the intervention, however, the majority of students demonstrated more coherent argumentation. In particular, *data* and *claims* were more effectively connected through deeper reasoning. This progress also likely resulted from the use of pre-structured argumentation cards.

Conclusion And Outlook

We conclude that implementing TAP implicitly through teaching materials such as argumentation cards may lead to an intuitively appropriate use of these tools, thereby laying the foundation for a more explicit implementation of TAP later on. This scaffolded intervention could lead to "[e]xercises that asked students to distinguish [between] claims, warrants and data", thereby to re-construct existing arguments, and thus providing a "foundation for more demanding exercises which asked students to construct their own arguments" (Osborne et al., 2016, p. 841).

Based on our findings, implementing TAP already shows promise in improving students' scientific argumentation skills – even within our short-term intervention, despite limitations such as time constraints, a small number of participants, and a generally high socio-economic status. Therefore, we are going to scale up our follow-up study with a larger, more diverse group of students. To this end, teaching materials will first be developed through design-based research (Bakker, 2018), in close collaboration with both students and teachers to iteratively refine the materials. This will be followed by a two-phase intervention study ($n \approx 150$). From a structural point of view, phase one will implement a simplified version of TAP, focussing on Claim, Data and Reasoning (based on the CER model of McNeill et al., 2006), first implicitly, then explicitly. From a content point of view, phase one focuses on chemistry specific content knowledge. An interactive learning video introduces the topic of human-induced ocean acidification and its effects on coral skeletons. Following this, students are asked to formulate written arguments – later extending to other calcifying organisms as well. Phase two will deepen TAP instruction by extending the CER model to include modal qualifiers and rebuttals. The SSI of human-induced ocean acidification will serve as the central content. Through structured discussions, students strengthen their argumentation skills, reflecting on their actions, and formulating personal courses of action – also considering the broader relevance for humans and ecosystems beyond coastal regions. Given the need for more chemistry-specific research on scientific argumentation in SSI-related subjects at the secondary level (Christodoulou & Grace, 2019), we anticipate that this contribution will offer valuable insights and stimulate further work in this research area.

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Explaining Facts About Electromagnetic Radiation In Podcasts: Students As Science Communicators

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Although students often construct explanations in class, they receive limited instruction in communication skills needed to articulate them effectively. In this project secondary school students (N=130-140, age 12-13) were put into the role of science communicators to produce science podcasts on topics of their choosing in electromagnetic radiation (EMR). Two test groups received different introductions prior to the production of podcasts: one on EMR content knowledge (CK) and the other on principles of good explanations. Assessing the depth and type of explanations revealed that students predominantly provide superficial and descriptive explanations. Interestingly, elevated CK did not result in higher-quality explanations. As numerous non-physics explanations were found, we analysed the contexts of the explanations in more detail. Two distinct genres of podcasts emerged: Nature of Science (NOS) podcasts (N=12), which embedded phenomena in a broader scientific context, and science podcasts (N=22), which provided science-based explanations of a phenomenon. We conclude that developing explanatory competence requires explicit instruction in communication skills rather than content knowledge alone. Podcasts offer a promising medium for fostering science communication competence and deepening students' engagement with NOS concepts.

Keywords: Science Communication Competence, Explaining, Podcast

Science Communication And Science Education

Fostering positive attitudes towards science as well as the construction of scientific knowledge are primary goals of both science communication research and science education research. However, the disciplines developed in separate directions. Thus, some scholars advocated for the rapprochement of the two disciplines (e.g., Baram-Tsabari & Osborne, 2015). Kohen and Dori (2019) therefore conducted a literature review to identify similarities and disparities between these "sister disciplines" (p. 526). A key finding concerns the different orientations of the two communities: "the science communication community mostly considers the process of communicating science to the public, whereas the science education community by and large focuses on the product—the knowledge and understanding of science that students gain as a result of learning and engaging with science" (Kohen & Dori, 2019, p. 545). By *process*, the authors refer to the way science content is communicated to the target audience, i.e., through various communication channels. While science communicators prioritize engagement and outreach, science educators (bound to formal settings and regulations) prioritize conceptual understanding and knowledge about science.

Our project seeks to bridge this gap by designing an intervention that targets both objectives: fostering *science engagement* through active participation in authentic communication practices while simultaneously developing students' *scientific knowledge* and *explanatory competence*. Specifically, we implement this approach through a workshop where students are put into the role of science communicators and create podcasts focused on Electromagnetic Radiation (EMR). In the next section, we briefly discuss the relevance of communication competence for science education and present the theoretical framework for the evaluation of the students' explanations.

The Role Of Communication Competence In Science Education

Through communication we make sense of the world, both through passive communication when i.e. obtaining information from written text or listening to explanations from others and through active communication when constructing our own explanations of observed phenomena. Furthermore, the relevance of communication competence becomes clear when examining key science education frameworks. For instance, communication competence is a core element of PISA, as scientifically literate students should be able to "explain phenomena scientifically", and "research, evaluate and use scientific information for decision making and action" (OECD, 2023, p. 9). Similarly, *constructing explanations* and *communicating information* are two out of the seven science practices included in the Next Generation Science Standards (NGSS, 2013). Moreover, explanatory and communication competencies are embedded in several school curricula worldwide, including those of Austria and Germany.

As a result, Kulgemeyer and Schecker (2013b) developed a constructivist model of communication competence. In this model, they distinguish between the subject adequacy and the addressee adequacy of a communication product. Communication between addressee and communicator is considered successful if the communication product is both addressee-adequate and subject-adequate. An addressee-adequate explanation considers the addressee's prior knowledge and interests, whereas subject adequacy refers to the correctness of the communicated information.

To analyse the subject adequacy of the students' explanations in this study, we examine the explanatory type and the explanatory depth. The explanatory type is linked to philosophical accounts of explanation described in detail by Braaten and Windschitl (2011). For this study, we adopted and slightly adapted their three levels of explanation: a) *descriptive explanations* which answer questions about the what of a phenomenon and describe it on the basis of patterns and surface features, b) *process-oriented explanations*, which answer questions about the how of a phenomena by invoking causes and simple if-then relationships, and c) *justifying explanations*, which answer questions about the why of a phenomenon by embedding it within the larger framework and drawing on theoretical concepts and laws. Because these three explanatory types do not capture the factual correctness of an explanation, we additionally examined its explanatory depth.

Research Gap And Research Question

Although the construction of explanations is crucial for the development of students' scientific literacy, the research field is still emerging. There are few existing studies, i.e., Helms (2017) developed a method to improve students' explanations to teach their peers, de Andrade et al. (2019) analysed students' written explanations in the context of chemistry, Alameh et al. (2023) compared explanations of students, teachers and experts and Kulgemeyer and Schecker (2013a) filmed students while explaining physics contents during a roleplay. They analysed the filmed explanations through a qualitative content analysis, focusing on the addressee-adequateness. The more beneficial categories an explanation counted, the better its quality. In this study, we aim to look deeper into the subject-adequacy of students' explanations to answer to what extent the CK affects the subject-adequacy of students' explanations.

In previous studies, students had to explain a certain phenomenon in a fixed setting. It remains unknown how students construct science explanations when put in the role of science communicators and choosing their own topics. We further aim to discover how the students' Content Knowledge (CK) and Communication Competence (CC)[1] affect the subject-adequacy of

[1] This influence of the CC on the explanations is not presented in this paper as the analysis is still in process.

the students' explanations and what contexts students choose for their podcasts as science communicators. The following questions guide our analysis:

RQ 1: Does elevated content knowledge result in increased levels of subject-adequacy of the students' explanations?

RQ 2: What contexts do students choose to communicate their physics knowledge in podcasts and how does the context affect the level of subject-adequacy of the students' explanations?

Research Design

The presented study is embedded in the bigger project *We talk about Science*. In this project, students are put into the role of science communicators and are tasked with the creation of science communication products. The products are presented during science communication events for the school community. To measure influences of the CK and the CC, we used two test groups and one control group. One test group received a communication training (CT group) comprising two school lessons in advance. The training consisted of theoretical knowledge on good explanations and various tasks to practise explaining. The other test group received four physics lessons on EMR prior to the Science Communication Workshops. In this article, we present the results of the produced podcasts with a focus of the students' CK and the podcasts' contexts. The study took place in the summer semesters of 2024 and 2025.

The Science Communication Workshops

The workshops in the second cycle in 2025 consisted of two days each comprising of three school lessons (each 50'). On the first day, students were briefly introduced to the goals of science communication (i.e., inform, entertain) and most important aspects to be considered when producing science communication products (i.e., choosing the right medium, tailoring the product to the target group). Afterwards, we presented the subject EMR to the students. This topic was chosen as we knew that the participating students had not received any training on EMR prior the intervention. Additionally, a teaching concept has been developed recently and evaluated for secondary school students by Zloklikovits (2022) in Vienna. Based on this concept, we introduced the students to some key ideas guided by a prepared power point presentation and interrupted by experiments (i.e., feeling versus seeing IR-radiation, observing the effect of UV-radiation on UV-sensible beads). Afterwards, we asked students how the new acquired knowledge should be explained to their peers. We introduced them to an explanation cycle (see Malotki et al., 2026) that was developed for the communication training. Subsequently, the students performed a paper pencil test (~20') to inquire about their CC and CK on EMR. The first day ended with the students choosing a topic in the field of EMR for their podcasts. We supported the selection process with a collection of links to information texts on the browser-based application *taskcards*. On a pinboard, we arranged the links according to the type of radiation discussed in the texts. The texts ranged from science communication texts from popular German speaking journals (i.e., *Spektrum der Wissenschaft*) to information texts from the *German Federal Office for Radiation Protection*, and physics texts especially for students (i.e., *www.leifiphysik.de*). In groups, the students planned their podcasts with the help of printed storyboards. On the storyboards, they focused on three to five main research questions, chose the genre of their podcast (i.e., interview or discussion format), and planned their explanations. The next day started with the students writing scripts on printed worksheets (~ 50'). In the next 50 minutes, students recorded their podcasts with their mobile phones or tablets using the App C*apCut* (free version). In the last 50 minutes, students edited and handed in their products. The workshop ended with listening and appreciating the students' podcasts. Also, the products were uploaded to our project website. This way, students and teachers could share the podcasts with the school community, family and friends.

In contrast to cycle II as described above, cycle I in 2024 provided maximum freedom for the students. The first day, we briefly introduced the students to the five key ideas of EMR based on the work of Plotz (2017, p. 5). Afterwards, the students posed three questions concerning EMR on their own and then chose one question in groups of three. The students did research on the internet to answer their chosen question. Using a storyboard and worksheets for preparing their scripts (similar to cycle II), they planned their science communication products in their preferred format: podcast, video or Instagram post. On the second day, students created their products. There was no exact timeline for each step of the production process and the teacher as well as the project team only assisted when help was required. The podcasts from cycle I will be examined together as one group (Z1).

Participants

In this study secondary students from the age of 12 to 13 participated (N = 130-140 students from six different classes). We chose middle school classes, as this is the most representative student population in Austria. One of the participating schools is located in Vienna and two in rural areas of Austria (Styria and Lower Austria). In contrast to the two schools in Styria and Lower Austria, the school in Vienna is a private school with a greater percentage of students with migration background. Next to the middle school in Upper Austria, there is a gymnasium–high achieving students are therefore more likely to attend the gymnasium next to the middle school. This information is important, as the location and separation of high-achieving and low-achieving students probably influenced the quality of the learning products.

Research Method

For this study we chose a mixed-methods design to analyse the quality of the students' podcasts and influences of the students' CK and CC. The students' podcasts were analysed by applying a structural thematic content analysis according to Kuckartz and Rädiker (2022). All podcasts (N = 34; duration: approx. one to five minutes) were transcribed and then uploaded to MAXQDA 2024. After transcribing the podcasts, each text was read and structured in explanation sequences. One explanation sequence (usually) equals the proposition of one student. Next, the type of each explanation sequence was determined using the deductive subcodes: descriptive, process-oriented, and justifying explanations. Subsequently, the depth of each student explanation was examined. We distinguished the four subcategories non-physics, insufficient, superficial and concept-oriented explanations. As this distinction resulted in a large number of non-physics explanations, we examined the context of each explanation in more detail and categorised them as dealing with physics, astronomy, history of physics, biology/medicine or Nature of Science (NOS). To have a better impression of the students' associations with science, we analysed NOS aspects that students addressed in their explanations. For this purpose, we used the already existing category system of Sattelkau (2021). She derived the NOS categories from diverse NOS concepts (i.e., Family Resemblance Approach, Whole Science) and reflections on science communication. In our analysis of the explanatory context of each explanation sequence and the number of NOS dimensions, three types of podcasts emerged: Physics Podcast, Biological Podcast and NOS Podcast.

To compare the different groups (CK group, CT group, Control group, and Z1 group) and the different types of podcasts, we calculated scores of the explanatory depth and explanatory type. Each proposition was assigned with one to three points, according to Table 1. The scores were calculated by dividing the sum of the points in depth and type through the number of explanation sequences in the podcast. For example, a podcast containing 4 propositions with three descriptive explanations and one justifying explanation results in six points divided by four, achieving a Type Score of 1.5. Similarly, the depth score of each podcast was calculated. To compare the groups,

we used quantitative tests such as ANOVA and Kruskal-Wallis-Tests. Furthermore, we compared the explanatory type and depth of the different podcast types using the Kruskal-Wallis-Test. Finally, the CK test on EMR was evaluated to compare the content knowledge of the three participating groups in the second cycle by running an ANOVA. To measure influences of the students' CK on the explanatory type and depth, we calculated correlations.

Table 1. Distribution of points according to the applied code.

	0 points	**1 point**	**2 points**	**3 points**
Explanatory Depth	Non-physics	Insufficient	Superficial	Concept-oriented
Explanatory Type	-	Descriptive	Process-oriented	Justifying

Results

Analysis Of The Explanations' Subject-Adequacy

We measured the level of the subject-adequacy by examining the type and depth of each explanation in the podcasts. As one can see in Table 2, most assertions were coded as descriptive explanations (n = 128). Those assertions deliver facts or describe observable phenomena, usually answering questions about the "what of a phenomenon". To a lesser extent, assertions were coded as process-oriented (n = 31) or justifying (n = 32). Process-oriented explanations answer questions to the "how of a phenomenon" and include i.e. if-then-clauses, showing simple relations between descriptions ("what") and their trigger ("how"). Justifying explanations answer questions of the "why of a phenomenon" and include causes, theoretical concepts and laws, usually signalled by the word "because". To compare the podcasts of the different groups, a type score of each podcast was calculated as described in the methods section. Running a Kruskal-Wallis Test, no difference was found between the four groups. Neither the communication training nor additional lessons on the concept of EMR seem to influence the explanatory type score.

For determining the depth of explanations, the inclusion of physic concepts, theory and laws as well as the correctness of the assertations was considered. At level zero, there are *non-physics explanations*, which address a physics phenomenon but do not provide a physics-based explanation (i.e., the history of the microwave oven and biological, medical subjects). At the next level are i*nsufficient explanations*, which present a physics perspective but are based on incorrect facts. The next level comprises *superficial explanations*, which include mostly correct facts but do not connect them to underlying physics concepts. In contrast, *concept-oriented* explanations contain physics concepts, draw conclusions, and rely on correct information only. In Table 2, one can find the distribution of codes concerning the explanatory depth. Calculating the depth score and comparing the measures of the groups did not show any differences when computing the Kruskal-Wallis Test, $\chi^2(3) = 3.764$, $p < .288$, $\varepsilon^2 = .114$. However, the CK group shows a slightly higher mean depth score when compared to the other groups. Especially when looking at Dunn's post hoc comparisons, the highest difference was found between the CK and Z1 group (p = .060). This might indicate that the additional lessons on EMR before the workshops had some effect on the explanatory depth. Moreover, the Z1 group that received the least information on EMR and the least guidance during the workshop achieved the lowest mean depth score of all groups, however we found no significant differences.

Influences Of The Students' Content Knowledge On The Explanations' Subject-Adequacy

In cycle II, the students took a brief paper-pencil test on EMR to measure influences of their CK on the explanation quality in their podcasts. After verifying the assumptions, we conducted an

ANOVA which revealed significant differences between the groups in their CK ($F(2, 68) = 10.02$, $p < .001$, $\eta^2 = .23$). Post hoc comparisons using Tukey's test showed that the CK group did not differ from the control group, $t(68) = .677$, $p = .777$, $d = .198$. However, we found significant

Table 2. Distribution of subcodes in the categories type and depth of explanations.

Type of Explanations

	Z1	C	CK	CT	Total
Descriptive	45	33	29	21	128
Process-oriented	8	6	8	9	31
Justifying	13	6	6	7	32
SUM	66	45	43	37	191
N = Documents	12	8	7	7	34

Depth of Explanations

	Z1	C	CK	CT	Total
Non-physics	30	17	9	9	65
Insufficient	7	0	7	9	23
Superficial	22	23	24	16	85
Concept-oriented	7	5	3	3	18
SUM	66	45	43	37	191
N = Documents	12	8	7	7	34

differences between the CK and CT group, $t(68) = 4.181$, $p < .001$, $d = 1.207$ and the control and CT group, $t(68) = 3.458$, $p < .003$, $d = 1.009$. Although the mean test score of the CK and control group was significantly higher than the test score of the CT group, comparing the depth scores in the section above, those groups did not present explanations in more depth. This is also evident when examining the correlations between one group's content knowledge and their explanatory type score, as we found no correlation between students' mean test scores and explanatory type or depth.

Context Of The Explanations

During the analysis of the explanations' depth, many non-physics explanations emerged. Nevertheless, the podcasts clearly referred to the field of science. Therefore, we added the main category NOS dimensions to explore which aspects of science the students discussed. As a first step, we decided for each proposition if a phenomenon was explained from a physics, astronomy, history of physics or biological/medical perspective. Explanations that did not fit into any of those categories were coded as NOS. Next, we analysed all explanations regarding NOS dimensions using the coding manual of Sattelkau (2021). An overview of found NOS dimensions in the podcasts and their adapted and summarized descriptions can be found in The Explanations' Subject-Adequacy In The Different Genres Of Podcasts

Given the non-normal distribution of the data, a Kruskal–Wallis test was used to compare the depth scores and type scores of the different genres of podcasts. The test showed that the three genres differed significantly in terms of the explanatory depth $\chi 2(2) = 14.333$, $p < .001$, $\varepsilon 2 = .434$. In Dunn's post hoc comparisons, Physics Podcasts achieved significantly higher depth scores than NOS Podcasts ($p < .001$, $rrb = .850$) and Biology/Medicine Podcasts ($p = .002$, $rrb = .800$). As expected, there were no significant differences comparing the types of explanations between the three genres, $\chi 2(2) = 1.971$, $p = .373$, $\varepsilon 2 = .060$. However, this result is not surprising, as NOS Podcasts and Biology/Medicine Podcasts count a higher number of non-physics explanations which are scored with zero points.

Table 3.

By comparing the number of applied codes in each podcast two main genres of podcasts emerged: Science Podcast (n = 22) and NOS Podcast (n = 12). Podcasts coded as Science Podcasts mainly focus on scientific explanations, either from a physics or biological/medical perspective on selected phenomena of EMR. Therefore, we distinguished between two subgenres depending on the referred science discipline: Physics Podcasts (n = 10) or Biology/Medicine Podcasts (n = 12). Physics Podcasts not only included science explanations but also the two dimensions NOS

Products and NOS *Production*. For instance, one group described how the sunlight can be used for energy production through *solar panels* (= subcode *Applications* in the dimension NOS *Products*). In Biology/Medicine Podcasts, we only discovered the NOS dimension *Products* with two subcodes *Applications* and *Risks and Benefits*. Several Biology/Medicine Podcasts presented the application of X-ray imaging, highlighting its benefits for medical examinations, as well as its risks. In contrast, NOS Podcasts displayed a variety of NOS dimensions, for example, they name different nationalities of scientists, describe collaborations and typical tasks of scientists (NOS *Actors*) and name different institutions around the world (NOS *Players*). In the main NOS Podcasts category, we discovered the subgenre History of Physics Podcasts. For instance, one group described the *coincidental* invention of the microwave oven, while another podcast tells the story of the *discovery* of infrared light in 1800 (NOS *Production*). Furthermore, we found evidence in the NOS Podcasts that, alongside the development of *Applications,* one goal of science is the acquisition of *Knowledge* (NOS *Products*).

The Explanations' Subject-Adequacy In The Different Genres Of Podcasts

Given the non-normal distribution of the data, a Kruskal–Wallis test was used to compare the depth scores and type scores of the different genres of podcasts. The test showed that the three genres differed significantly in terms of the explanatory depth $\chi^2(2) = 14.333$, $p < .001$, $\varepsilon^2 = .434$. In Dunn's post hoc comparisons, Physics Podcasts achieved significantly higher depth scores than NOS Podcasts ($p < .001$, $r_{rb} = .850$) and Biology/Medicine Podcasts ($p = .002$, $r_{rb} = .800$). As expected, there were no significant differences comparing the types of explanations between the three genres, $\chi^2(2) = 1.971$, $p = .373$, $\varepsilon^2 = .060$. However, this result is not surprising, as NOS Podcasts and Biology/Medicine Podcasts count a higher number of non-physics explanations which are scored with zero points.

Table 3. Short descriptions of the NOS dimensions, adopted and adapted according to Sattelkau (2021). Specific examples found in the products are given in brackets.

NOS Dimensions	Products (n=71)	Knowledge (n=6)	One intention is the generation of knowledge, differentiation between models, theories and laws (i.e., finding out the origin of the universe)
		Applications (n=65)	Specific applications or technologies, optimization of applications and visions of future applications; Risks and benefits for humans and the environment (i.e., risks of x-ray imaging)
	Players (n=31)	Politics (n=1)	Diverse political actors, Scientific findings inform political decisions, politics can influence the direction of scientific research, i.e. through financing (i.e., Federal Office for Radiation Protection)
		Society (n=10)	Influences of society's needs, development through science, science communication, trust and mistrust (i.e., what radiation types are dangerous, radiation protection)
		Science (n=19)	Institutions, Disciplines, Financing of Science and Lobbying (i.e., scientific facilities around the world, collaborations in large science projects)
		Industry and Economy (n=1)	Influences of industry and economy on scientific projects, input and output of science for industry (i.e., invention of the microwave in the laboratory of an armaments industry)
	Actors (n=40)	Personnel Diversity (n=19)	Scientists have various cultural, religious, gender backgrounds and nationalities, different professions (i.e., physicists)
		Activities (n=15)	Scientists produce knowledge through observing, examining, measuring, … name substances, planets etc.
		Characteristics (n=2)	Scientists have different personalities, typical and atypical characters (i.e., curiosity), they experience success and failure, have vast expertise
		Social Interactions (n=4)	Scientists work together, discuss findings in (inter-)national conferences, use peer reviews, award prizes for outstanding work or name i.e. methods after scientists (i.e., Planck Telescope)
	Production (n=24)	Methods, mechanisms and practices (n=18)	Nature of scientific inquiry, different scientific methods, empirical evidence, formulation and testing of hypotheses (i.e., drawing on empirical evidences, presenting different scientific methods)
		Development and Time (n=6)	Scientific findings take time, there are highs and lows, errors and irregularities (i.e., coincidental invention of microwave oven, year dates)

Discussion

Students Mostly Provided Descriptive And Superficial Explanations

Although children are usually interested in more detailed information when confronted with explanations (*Why is that so?*), they did not show the same inquisitiveness about their own explanations in the analysed podcasts. Students mostly offered *descriptive explanations* and rarely provided *justifying* or *process-oriented explanations*. However, in the second cycle, we explained that in science, a claim is always followed by justifications. This was also one of the points highlighted in the communication training. Nevertheless, the CT group did not provide more justifications than the other groups. We do not know whether students are satisfied with the quality of their explanations or if they simply were overwhelmed by all the steps they had to take in our workshop. It is also possible that students lacked detailed knowledge of the phenomenon to be explained. Note that students did not show signs of time pressure during the research phase.

Furthermore, all groups tended to provide predominantly *superficial explanations*. We anticipated that the CK group might provide explanations in more depth, since they could rely on key ideas and experiences from the lessons on EMR before the workshop. However, the CK group did not provide a higher number of *concept-oriented explanations* than the other groups. This might indicate that students need some kind of guidance to connect prior knowledge to new information gathered from research. Additionally, Schecker and Höttecke (2021) report that in students' explanations claims often lack the connection to physics principles. To guide students in this process, Tschentscher and Berger (2016, as cited in Schecker & Höttecke, 2021, p. 500) developed the methodological tool "Explanatory Chain" (Erklärkette) to support students in formulating subject-adequate explanations.

Interestingly, only about 12 % (n = 23) of the propositions were coded as insufficient, which means that explanations based on wrong facts (i.e., humans cannot see but feel UV radiation, or gamma radiation is radioactive) were not predominant in the student-created podcasts. Nevertheless, we found a large number of explanations that were not physics related. This raises the question of whether students avoid intensive engagement with physics topics, preferring to talk about related sciences (i.e., biology or medicine) rather than explain phenomena from a physics perspective.

Influences Of The Content Knowledge On The Quality Of Explanations

In this study, we did not find statistical evidence that higher levels of CK resulted in higher quality of explanations. This was measured by evaluating the subject-adequacy in terms of the type and depth of explanations. The mean scores of the groups on the CK-test neither influenced the depth score nor the type score. This might indicate that it does not suffice to provide students with information about a certain topic to provide high quality explanations. This is in line with previous studies on CK and its influences on students' communication skills (Kulgemeyer & Schecker, 2013b). Similar results were found for teachers, needing a certain level of pedagogical content knowledge (PCK) to use their CK for delivering high-quality explanations (Kulgemeyer & Riese, 2018). Perhaps students too must develop communication competence skills in science education in order to provide high-quality explanations. Interestingly, students are usually tasked with the formulation of explanations during science lessons or in exams without being prepared with explanatory skills. As part of this study, we therefore developed and evaluated a communication training that focused on the addressee-adequacy of explanations. So far, the CK group has not shown better results in terms of the subject-adequacy of explanations. However, the results regarding the influences of the CC on the subject-adequacy as well as influences of the communication training on the addressee-adequacy are still being processed.

A deeper analysis of propositions coded with the subcategory non-physics opened a new perspective on the student-produced podcasts. We found two main genres of podcasts, Science Podcasts with the focus of explaining phenomena scientifically (at an age-adequate level) and NOS Podcasts that embed a topic in the field of EMR in a broader picture and address various aspects of science. In this category, we found the subgroup History of Science Podcasts. This is especially interesting, as one propagated way of teaching NOS is through the History of Science approach. Regarding the distribution of genres in the different groups, most NOS Podcasts were found in cycle II (n = 10) in the control group (n = 5). This might be influenced by the fact that we offered them a diverse range of topics concerning EMR on *taskcards*. However, in the end the students chose the topic by themselves. Furthermore, ten out of twelve Physics Podcasts were also created in cycle II. One might anticipate that most of the Physics Podcasts were produced by the CK group, however, in each group of cycle II we found three or four Physics Podcasts. Interestingly, eight out of twelve Biology/Medical Podcasts were created in cycle I. Apparently, students avoid deeper engagement with a chosen topic from a physics perspective, especially if they are not confronted with pre-selected topics/texts.

Limitations

Please consider that there are several limitations in this study:

- The correlations between the CK and the explanation quality in the first cycle is based on a small number of students (N = 71). The analysis of the explanatory type and depth score is based on both cycles with a sum of n = 34 podcasts. However, this is an exploratory study with a focus on the development of teaching materials.
- The findings reported are preliminary, as this is part of the ongoing dissertation project of the first author. Intercoder agreement on the coded data is planned for summer 2026.
- The groups included are not easily comparable, as the students have different socioeconomic backgrounds. Additionally, two of the participating middle schools are located next to a gymnasium. Consequently, high-achieving students are more likely to attend the gymnasium. In contrast, there is no gymnasium near to the third middle school (control group). This may explain why the control group performed better in the CK test. The choice of different schools was made due to the project's focus on science communication and the goal of greater outreach.
- As the podcasts are created in groups, it was not possible to compute correlations between individual CK scores and their skills in providing subject-adequate explanations.
- The used CK test on EMR is based on previous work of Zloklikovits (2024). The adapted and used items were not evaluated in advance. Also, the test only consisted of four items due to time restrictions.

Conclusion

Although we established considerable high standards for the students, they delivered commendable products in a short period of time and demonstrated strong engagement during the podcast production on the second day of the workshops. Incorporating science communication practices, particularly divers communication channels and attention to *communication processes*, appear to be effective approaches to engage students with science. While approximately a third of the created podcasts focused on physics explanations to present a chosen topic in the field of EMR another third of the podcasts focused on facts *about* science. This might indicate that the production of podcasts might be a beneficial way to teach NOS, especially when addressing NOS

explicitly. However, aiming at the production of Physics Podcasts, students need more guidance in obtaining information and translating gathered information into valuable science explanations. Formulating subject-adequate explanations is a skill that must be learned. One way of supporting this process is through the explanatory chain developed by Helms (2017). The analysis of the explanations' addressee-adequacy and influences of the developed communication training on the students' explanations are still ongoing. So far, this article presented a useful way of analysing the subject-adequacy in terms of type and depth of explanations. Those categories along with characteristics of the addressee-adequacy will be part of a diagnostics tool for analysing students' explanations. To conclude, we think that next to a certain level of CK, students should be prepared with explanatory skills in science education as are teachers with PCK. By strengthening students' communication skills, we enable them to express and share their knowledge effectively.

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Argument Construction System 'Argu-Made 2.0' To Support The Examination Of Evidence And Scientific Judgement Regarding The Bioaccumulation Of Pufferfish Toxins

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Japanese primary school education is required to develop the ability to make scientific judgements about food safety and prevent food poisoning. For example, the consumption of pufferfish requires a scientific understanding and judgement of the bioaccumulation of pufferfish toxins. An argument consisting of 'claim – evidence – reasoning' is effective in using scientific understanding, and, in particular, the appropriate use of evidence is considered important. Therefore, this study developed an argument construction support system 'Argu-made 2.0', and conducted a class using this system and simulators by Matsuyama et al. (2023) promoting understanding of the bioaccumulation of pufferfish toxin, and the effectiveness of Argu-made 2.0 was evaluated. This class was conducted for sixth-grade food-chain studies. Students learned about the bioaccumulation of pufferfish toxins using simulators and constructed arguments while examining the evidence in Argu-made 2.0. The effectiveness of Argu-made 2.0 was evaluated from two perspectives: 'examination of evidence' and 'achievement of scientific judgement'. In 'examination of evidence', the process of using evidence appropriately in Argu-made 2.0 was analysed, while in 'achievement of scientific judgement,' the content of the students' arguments was analysed. The results showed that 48 [87%] students selected appropriate evidence, and 42 [76%] constructed arguments by correctly constructing all elements. These results indicate that Argu-made 2.0 was effective in supporting sixth-grade students in considering appropriate evidence and in making scientific judgements about the presence or absence of pufferfish toxins.

Keywords: Argument, Primary school, Argu-made 2.0

Introduction

Japanese primary school education is necessary to make effective scientific judgements about food behaviours, which is crucial for food safety especially preventing food poisoning. However, not only in Japan, recent studies have indicated that many consumers make incorrect judgements about food safety due to limited knowledge and awareness (e.g., Sharif & Al-Malki, 2010). There is a growing need for teaching methods that enable primary school students to learn to handle food safely and make informed judgements using this knowledge.

One example of scientific judgement regarding food safety is food poisoning by pufferfish toxins. In this case, a scientific understanding of the bioaccumulation of pufferfish toxins and a scientific judgement regarding the safety of consuming pufferfish by applying this understanding are necessary (e.g., Malloggi et al., 2023). Students must understand how the concentration process works to gain a scientific understanding of pufferfish toxin bioaccumulation. The simulator developed by Matsuyama et al. (2023) to understand the bioaccumulation of pufferfish toxins was effective in promoting this process. Developing the ability to form scientifically valid ideas (claims) is key to making scientific judgements. Arguments structured as 'claim (answer to a question) - evidence (experimental results) - reasoning (scientific principle)' have proven effective (e.g., Kamiyama et al, 2015; Iordanou et al, 2019). In particular, since the use of

appropriate evidence provides higher scientific credibility and validity to one's claims, it is important to consider the appropriateness of evidence in terms of it being obtained for proper purposes and methods and it being linked to one's claims while being based on theoretical support (scientific conventions) (Duncan et al., 2018).

Matsuyama et al. (2024a) developed an argument construction support system, 'Argu-made', to help users share, compare, and examine evidence online to promote the appropriate use of evidence. Matsuyama et al. (2024b) developed and evaluated a teaching method to encourage scientific judgement on the subject of bioaccumulation of pufferfish toxins, using a simulator developed by Matsuyama et al. (2023) in combination with arguments consisting of 'claim-evidence-reasoning'. The results showed that some students did not appropriately use their knowledge of the mechanism of bioaccumulation in their scientific judgements, indicating the need for improved instruction on the structure of evidence and reasoning.

Therefore, this study focused on examining this evidence, which was one of the challenges identified by Matsuyama et al. (2024b). To improve evidence examination, support is needed to allow opinions on the appropriateness of evidence to be shared and compared online and reconsidered from multiple perspectives. Therefore, we improved Argu-made by Matsuyama et al. (2024a) and developed an argument construction support system called 'Argu-made 2.0' that has the functions to realise these improvements. Unlike traditional paper media, this system enables asynchronous commenting based on individual progress, improving learner participation. Another feature is that past opinions can be confirmed and revised based on the comment history. This study aimed to develop and implement an instructional method using the simulator by Matsuyama et al. (2023) and Argu-made 2.0, and to analyse the effectiveness of this method by focusing on the process of examination of evidence by students and the achievement level of scientific judgement.

Research Question

This study verified the effectiveness of Argu-made 2.0. The two research questions are as follows:

Did Argu-made 2.0 support the evidence for bioaccumulation of pufferfish toxin?

Was Argu-made 2.0 effective in achieving scientific judgement?

Argument Construction Support System 'Argu-made 2.0'

Argu-made 2.0—a system developed using the no-code application development tool 'Adalo'—supports the construction of an argument consisting of 'claim (answer to a question) - evidence (experimental results) - reasoning (scientific principle)'. Figure 1 shows the home screen of Argu-made 2.0. Using the 'Decision of Claim (①)' function, users decide on the claim (the answer to the question) and make a plan for the construction of the argument, such as considering the characteristics of evidence to enhance its scientific reliability and validity (hereinafter referred to as 'appropriate evidence'). Using the 'Examination of the Evidence (②)' function, they can compare evidence and discuss the appropriateness of each evidence while considering the evidence to be used in the argument. The 'Examination of the Reasoning (③)' function allows them to construct reasoning that strongly supports the scientific credibility of their claims (hereafter referred to as 'appropriate reasoning'), just as when considering the selection of evidence.

Figure 1. Home screen.



Selecting 'Examination of the Evidence (②)' takes the users to the screen shown in Figure 2. Several pieces of evidence are submitted and shared here. They can extract appropriate evidence with a good mark (②-2) using the characteristics of the appropriate evidence noted in ②-1 as a hint. Furthermore, by selecting the comment mark (②-3) on each piece of evidence, they can move to the screen shown in Figure 3 to examine the appropriateness of the specified evidence. They can share their opinions, such as reasons, with others using the comment-sending function (②-4), and check the contents in the list (②-5).

Figure.2 Screen for submitting and sharing evidence



Figure.3 Screen for discussing the appropriateness of evidence



Overview Of The Class

A four hour long class was conducted by the second author in the science course 'Connections among living creatures' for 55 sixth-grade students (11–12 years old). Students had already studied the food-chain on land and in rice paddies. At the beginning of this class, they also knew that pufferfish toxin is not produced endogenously but by marine bacteria. They were asked the following learning question: 'If only marine bacteria were not eaten, would pufferfish be poisonous?' They made scientific judgements about the presence or absence of pufferfish toxins in the following two scenarios.

In Scenario 1, using the simulator and the knowledge of the content of the previous class, the students were asked to organise the food-chain with the five creatures (pufferfish, crabs, starfish, clams, and marine bacteria) and understand the basic mechanism of bioaccumulation: All the toxin in the prey is absorbed into the predator's body. In Scenario 2, through simulations, they confirmed the mechanism of bioaccumulation: The amount of toxin accumulated depends on what and how much a predator preys on, and more toxin is accumulated as it gets closer to the top of the food-chain. Subsequently, they constructed arguments using Argu-made 2.0. First, the students were given the prospect of constructing the argument by deciding their claim with the function of 'Decision of Claim (① in Figure 1)'. Next, they submitted and shared their evidence using the function of 'Examination of the Evidence (② in Figure 1)', and extracted the evidence they considered appropriate with a good mark (②-2 in Figure 2). Only one appropriate piece of evidence was selected when discussing the appropriateness of each piece of evidence with comments (②-4, 5 in Figure 3). Finally, the function of 'Examination of the Reasoning (③ in Figure 1)' was used to construct the appropriate reasoning just as when considering the selection of evidence.

Analysis

The class was evaluated from two perspectives: 'examination of evidence' and 'achievement of scientific judgement'. In the 'examination of evidence', the extraction of evidence with good marks (②-2 in Figure 2) from students' activity history in Argu-made 2.0 in scenario 2 was analysed by classifying the students into four types (Table 1).

For the 'achievement of scientific judgement', the content of the students' arguments in scenario 2 were analysed by scoring them, and their judgements about the presence or absence of pufferfish toxins were evaluated. We scored the claims, evidence, and reasoning independently on a 1-point scale, with the sum of the scores on a 3-point scale, based on a rubric. Concerning claim, one point was awarded if the student was able to write 'poisonous' in response to the question: If only marine bacteria were not eaten, would pufferfish be poisonous? Concerning evidence, one point was awarded if the student was able to select the experimental result: the pufferfish fed on zero marine bacteria and at least one other creature of one or more species. For reasoning, one point was awarded for correctly describing the basic explanation of how bioaccumulation works: All the toxins in the prey are absorbed into the body of the predator.

Results

From the 'examination of evidence' section, Table 1 shows the status of evidence extracted with good-mark. Of the students who selected appropriate evidence, Type A (42 [76%]) extracted only appropriate evidence with good marks. Type B (6 [11%]) selected appropriate evidence at the end, although they extracted appropriate and inappropriate evidence with good marks.

Among the students who ultimately failed to select appropriate evidence, Type C (2 [4%]) extracted appropriate and inappropriate evidence with good marks. Type D (4 [7%]) extracted all

inappropriate evidence with good marks. Type E (1 [2%]) did not select anything at the extraction or selection stage.

In the 'achieving scientific judgement' section, 54 out of 55 [98%] students received a score of 1 for the claim, 48 [87%] for the evidence, and 47 [85%] for the reasoning in each component. In addition, 42 students [76 %] correctly constructed all the elements (students who scored a perfect score of 3). Most students used the food-chain and bioaccumulation mechanisms to make scientific judgements regarding the presence or absence of pufferfish toxins while providing evidence of appropriate simulation results.

Table 1. Extraction of evidence with the good-mark to its adoption into the argument

Type	Number of students [The ratio]
A: All evidence given a good mark is appropriate, and the appropriate evidence is ultimately selected.	42 [76 %]
B: The evidence given a good mark is a mixture of appropriate and inappropriate evidence, but the appropriate evidence is ultimately selected.	6 [11 %]
C: The evidence given a good mark is a mixture of appropriate and inappropriate evidence, and the inappropriate evidence is ultimately selected.	2 [4 %]
D: All evidence given a good mark is inappropriate, and the inappropriate evidence is ultimately selected.	4 [7 %]
E: None of the evidence was given a good mark, or no evidence was ultimately selected.	1 [2 %]

Discussion

Argu-made 2.0 developed in this study was able to support the examination of evidence regarding the bioaccumulation of pufferfish toxins. Based on the status of the extraction of evidence with good marks, Argu-made 2.0 effectively helped sixth-grade students examine appropriate evidence. This effectiveness was attributed to Argu-made 2.0 encouraging the step-by-step selection of evidence using the good-mark function and supporting discussion its appropriateness during the selection process.

Furthermore, Argu-made 2.0 was effective in achieving scientific judgements. Most students used food-chain and bioaccumulation mechanisms to make scientific judgements about the presence or absence of pufferfish toxins while providing appropriate evidence. This success was likely because the selected evidence could be uploaded immediately to the argument, reducing the workload for the students and allowing them to focus on constructing arguments without interruptions. Additionally, since Argu-made 2.0 allows repeated modifications after uploading, this feature likely encouraged the students to re-examine the appropriateness of their evidence.

Future studies should investigate these factors in greater detail through questionnaires and follow-up interviews.

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Gender Differences In Science Groupwork Participation: Exploring Students' Voices Using Automatic Speech Recognition And Social Network Analysis

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This study explores gendered participation patterns in secondary school science group work by integrating Automatic Speech Recognition (ASR) and Social Network Analysis (SNA) in authentic classroom settings. Audio data were collected during science activities involving 16 students in a Finnish secondary school, using individual microphones with separate-channel recording to capture student speech. ASR was applied to generate time-stamped transcriptions and speaker labels, and interaction networks were subsequently constructed using SNA to identify participation patterns and student roles. Student speech was also manually coded into functional categories to examine discourse roles over time. The results demonstrate that ASR, when combined with individual microphone systems, can accurately differentiate speakers and capture student interactions in natural classroom environments. SNA effectively identified central and peripheral participation roles, while discourse analyses revealed how gender, science identity, and extroversion intersect to shape students' participation patterns. Although exploratory, this study highlights the methodological potential of combining ASR and SNA for fine-grained and scalable analyses of equitable participation in science classrooms.

Keywords: gender difference, automatic speech recognition, social network analysis

Introduction

Gendered Participation In School Science Group Work

Over the last decade, in many countries including Finland, female students have outperformed male students in school science subjects (OECD, 2016; 2023). In addition, previous studies indicate that female students tend to report stronger preferences for collaboration (Li et al., 2021) and higher levels of extroversion than their male peers (Weisberg et al., 2011). Taken together, these characteristics—higher academic performance, greater cooperativeness, and stronger extroversion—would suggest that female students are likely to participate actively in science group work.

Contrary to this expectation, participation in science group work often follows gendered patterns. Research consistently shows that boys tend to dominate group interactions and assume leadership roles, whereas girls are more frequently positioned at the periphery of group activities (Wieselmann et al., 2020). One potential explanation for this pattern lies in differences in science identity. Boys, on average, report higher levels of science identity, encompassing recognition, confidence, interest, and perceived competence, compared to girls (Williams & George-Jackson, 2014).

However, science identity alone does not fully explain observed participation dynamics. Empirical evidence suggests that some girls with high levels of science identity still participate passively in group work, while some boys with relatively low science identity engage actively (Kang, 2023). Moreover, it remains underexplored why girls' reported extroversion and collaborative preferences are not consistently manifested in their observable participation during science group activities. These inconsistencies point to a need for more nuanced analyses that consider the intersection of gender, science identity, and personal characteristics in shaping participation patterns.

To date, however, most studies investigating gendered participation in science group work have relied on small samples and labor-intensive manual observation or coding. While such approaches have provided important insights into classroom interaction, they offer limited temporal resolution and constrain the ability to examine participation patterns systematically across groups and contexts. There is therefore a clear need for methodological approaches that enable scalable, fine-grained analyses of student participation in authentic classroom settings, making it possible to link individual dispositions with observable interactional roles and participation trajectories.

Emerging Technologies For Capturing Participation Patterns

Traditionally, participation patterns during group work have been examined through direct classroom observation or video-based coding schemes, both of which are time-intensive and limited in scalability (e.g., Wieselmann et al., 2020). While these approaches allow for rich qualitative interpretation, they pose challenges for capturing fine-grained interactional dynamics across larger samples and multiple classroom contexts.

Recent advances in educational data science have introduced computational approaches that offer new possibilities for analysing classroom interactions in more systematic and scalable ways. One such approach is Automatic Speech Recognition (ASR), which enables the automated transcription of spoken interactions and the quantification of verbal participation (Jensen et al., 2021; Pugh et al., 2021). In classroom research, ASR has primarily been applied to teacher talk, as it is logistically easier to equip a single teacher with a high-quality microphone than to provide individual recording devices for students (Jensen et al., 2021). Only a small number of studies have applied ASR to student speech. For instance, Pugh et al. (2021) examined collaborative dialogue among students aged 12–15 using headset microphones; however, their data were collected outside natural classroom environments, with students interacting in pairs over Zoom. Consequently, the potential of ASR to capture student participation in authentic, face-to-face science group work remains underexplored.

While ASR enables the identification of who speaks and how much, it provides limited insight into the relational structure of interactions within a group. To address this limitation, Social Network Analysis (SNA) has increasingly been adopted in educational research as a powerful analytical framework for examining interactional patterns among learners (Saqr et al., 2020). SNA conceptualizes classroom interactions as networks, where students are represented as nodes and communicative exchanges as ties. This approach makes it possible to identify participation structures, such as central or peripheral roles, leadership, and dominance, that may not be readily visible through frequency-based measures alone.

In the context of group work, SNA has been used to examine collaboration quality, knowledge construction, and social positioning within learning groups (Saqr et al., 2018; 2020). Importantly, SNA offers a theoretically grounded way to operationalize participation as a relational phenomenon rather than an individual attribute, making it particularly well suited for investigating gendered participation patterns.

Integrating ASR with SNA offers a promising methodological advancement. ASR can provide automated, fine-grained data on verbal interactions, while SNA can model these interactions as dynamic networks that reveal students' participation patterns and roles within group work. Despite this potential, empirical studies that combine ASR and SNA to analyse student participation in natural classroom settings remain scarce. This study seeks to address this gap by leveraging the complementary strengths of ASR and SNA to examine gendered participation patterns in science group work.

Research Aim And Questions

Addressing these gaps, the present study aims to examine students' participation patterns during science group activities conducted in natural classroom settings. Specifically, it investigates how gender, science identity, and personality characteristics—particularly extroversion—are associated with students' participation patterns and roles within group work. Methodologically, this study explores the integration of ASR and SNA as complementary tools for identifying participation structures and interactional roles in an automated and scalable manner.

The study is guided by the following research questions:

RQ1. Can ASR capture and differentiate students' speech during science group activities in natural classroom settings?

RQ2. Can SNA effectively identify participation patterns and student roles within science group work?

RQ3. How are gender, science identity, and personality traits (extroversion) related to students' participation patterns and roles in science group activities?

Methods

Sample, Data Collection, And Measures

The study was conducted with high school students participating in a mandatory two-day science project on sustainability in Finland. A total of 28 students took part in the project, of whom 16 volunteered to have their voices recorded during the first two-hour brainstorming session. These 16 students were organized into four groups, each consisting of four members. Three groups comprised two female and two male students, while one group consisted of one female and three male students.

To capture individual student speech during group work, each participating student was provided with a wireless microphone. Audio signals were recorded on separate channels using an LR20 mixer to ensure high-quality speech input suitable for ASR processing. After recording, the audio channels were grouped according to team membership and merged into four final audio files—one per group—while preserving channel-level information for speaker identification.

In addition to audio data, students completed questionnaire measures assessing science identity and personality characteristics, including extroversion. These self-report measures were used to contextualize participation patterns identified through ASR and SNA and to explore potential associations between individual characteristics and participation roles.

Data Analysis

ASR processing generated time-stamped transcriptions and speaker labels, which served as the basis for constructing interaction networks for SNA. To address RQ1, the quality of ASR outputs was evaluated using two complementary metrics: Word Error Rate (WER) and Diarization Error Rate (DER). WER quantifies the proportion of incorrectly recognized words relative to a human reference transcript, with lower values indicating greater transcription accuracy. In speech recognition research, lower WER values (e.g., below approximately 20–30% in noisy multi-speaker environments) have been considered acceptable for interaction-level analysis rather than for perfect lexical accuracy alone (Attia et al., 2023).

On the other hand, DER measures the proportion of total recording time that is incorrectly attributed to speakers, combining false alarms, missed speech segments, and speaker confusions into a single error metric. DER is the most widely used metric for evaluating speaker diarization systems, especially in multi-speaker contexts where correctly identifying "who spoke when" is

critical for interaction analysis. In natural, spontaneous speech environments such as classroom group discussions, DER values up to mid-30% range have been reported in recent diarization research as indicative of a feasible diarization system for exploratory interaction analysis (Wang et al., 2024).

The outputs of ASR (time-stamped transcriptions and speaker attributions) were used to construct participation networks for SNA. In these networks, students were represented as nodes, and ties were defined based on temporal co-occurrence of speech segments and turn-taking interactions. SNA indicators (e.g., degree and eigenvector centrality) were then used to distinguish between more central and more peripheral participants within each group, addressing RQ2.

Survey data on science identity and personality traits were integrated with ASR- and SNA-derived indicators to explore associations between individual characteristics (gender, science identity, extroversion) and participation patterns, addressing RQ3. Given the pilot nature of the study and the small sample size, these analyses were exploratory and aimed at identifying preliminary trends rather than testing causal relationships.

To complement the automated analyses, a manual content analysis of student speech was conducted. Each utterance was coded into one of six functional categories: directing, elaborating, questioning, sharing, disagreeing, or agreeing. This coding provided (a) richer interpretive insight into participation patterns beyond structural measures, and (b) a labelled dataset for future development of machine learning models for automated speech function classification. In the present pilot study, the manually coded speech functions were incorporated into the participation analysis to capture both quantitative interaction structures and qualitative discourse roles.

Results

RQ1. Can ASR Capture And Differentiate Students' Speech During Science Group Activities In Natural Classroom Settings?

Audio data were collected from four student groups in a secondary school science classroom. To address RQ1, an initial performance evaluation was conducted using the audio data from the first group to compare several commercially available ASR systems, including Whisper, Google Cloud Speech-to-Text, AWS Transcribe, and AssemblyAI. The comparison focused primarily on the systems' ability to accurately differentiate between individual speakers in a natural classroom environment. Based on this evaluation, AssemblyAI was selected for subsequent analyses, as it demonstrated the highest speaker differentiation accuracy.

For the first group, ASR performance was quantitatively evaluated using WER and DER. The word-level comparison between ASR output and human transcripts yielded a WER of approximately 2.1% (63 word errors out of 3001 reference words), indicating very high lexical accuracy. At the utterance level, comparison of human and ASR speaker labels resulted in a confusion-based DER of approximately 19.5%, corresponding to a speaker attribution accuracy of about 80.5%. These values substantially exceed typical feasibility thresholds reported for classroom-based, multi-speaker ASR applications, where considerably higher error rates are often considered acceptable for participation-level analysis. Following this initial evaluation, AssemblyAI was applied to the remaining three groups.

Despite the overall high accuracy, minor errors were observed in both word recognition and speaker identification. For example, as shown in Table 1, in Occurrence 1, the utterance "I don't have any ideas" was incorrectly transcribed as "I do have any ideas," representing a word-level recognition error. In Occurrence 298, an utterance was incorrectly attributed to a group member when it originated from a brief interruption by a neighboring group, resulting in a speaker

attribution error. Such cases were rare and did not meaningfully affect the identification of speaker turns or overall participation patterns.

As illustrated in Table 1, the ASR system detected approximately 300 speech occurrences among the four members of the first group, providing detailed information on speech duration and speaker identity. Each entry includes an occurrence number, timestamps marking the start and end of speech, an assigned speaker label (A, B, C, or D), and the corresponding transcription.

Overall, the results demonstrate that ASR can capture and differentiate students' speech with high accuracy during science group activities in natural classroom settings. The high level of performance observed in the initial evaluation, together with consistent outputs across all groups, supports the feasibility of using ASR for analysing student participation patterns, addressing RQ1.

Table 1. Sample conversation excerpt from ASR output.

Occurrence	Duration	Speaker: Statement
1	00:00:01,439 --> 00:00:03,020	Speaker A: I do have any ideas.
2	00:00:06,879 --> 00:00:10,259	Speaker B: What kind of inequality do you want to focus on?
3	00:00:12,480 --> 00:00:15,660	Speaker A: Unfortunately, I haven't experienced any inequality.
4	00:00:20,239 --> 00:00:24,300	Speaker C: Last year they did the accessibility.
5	00:00:24,719 --> 00:00:50,466	Speaker D: The first thing that pops into my mind is like, you know, language inequalities, you know, like if you don't speak Finnish, like, how much that sets you back. Like in general, living in XXX or in Finland, of course it like depends on the area. Like in XXX, like, there might be more English translations and stuff, but like, think about how hard it is to participate in everything.
….	….	….
298	00:46:16,420 --> 00:46:57,019	Speaker D: How are you guys doing? What is it? What is it? That is interesting. That is such a good idea. I know. Great.
299	00:46:59,159 --> 00:47:13,619	Speaker A: Yeah. We're doing about nutrition in relation of malnutrition to poverty and reinforcing this free school food with nutrients which are, like, less common in the poorer.

RQ2. Can SNA Effectively Identify Participation Patterns And Student Roles Within Science Group Work?

Following ASR-based transcription and speaker identification, Social Network Analysis (SNA) was conducted to examine interaction patterns within student groups. Due to space limitations, the results presented here focus on a single 45-minute recording from Group 1, consisting of two male and two female students. The speakers' characteristics were as follows: Speaker A (Male 1, high science identity, extroverted), Speaker B (Female 1, low science identity, introverted), Speaker C (Male 2, average science identity, extroverted), and Speaker D (Female 2, average science identity, extroverted).

Frequency Of Speech Transitions And Speaking Duration

A total of 299 speech transitions were identified and ranked by frequency (Table 2). The most frequent transitions occurred between Speaker A and Speaker C (A→C: 70; C→A: 66), indicating that a substantial portion of the discussion was concentrated between the two male students. The next most frequent transitions were between Speaker C and Speaker D (C→D: 50; D→C: 45), suggesting that Speaker C actively engaged with multiple group members. In contrast, transitions involving Speaker B were rare, with only three transitions observed between Speaker C and Speaker B and between Speaker B and Speaker A, indicating limited participation and a

peripheral role in the discussion.

Analysis of speaking duration further supported these patterns. Speaker C had the longest total speaking time (751.52 seconds), followed by Speaker D (571.53 seconds) and Speaker A (564.83 seconds), whereas Speaker B spoke substantially less (119.76 seconds). Together, the high frequency of transitions and extended speaking duration position Speaker C as the most central participant in the group, while Speaker B appears comparatively marginalized.

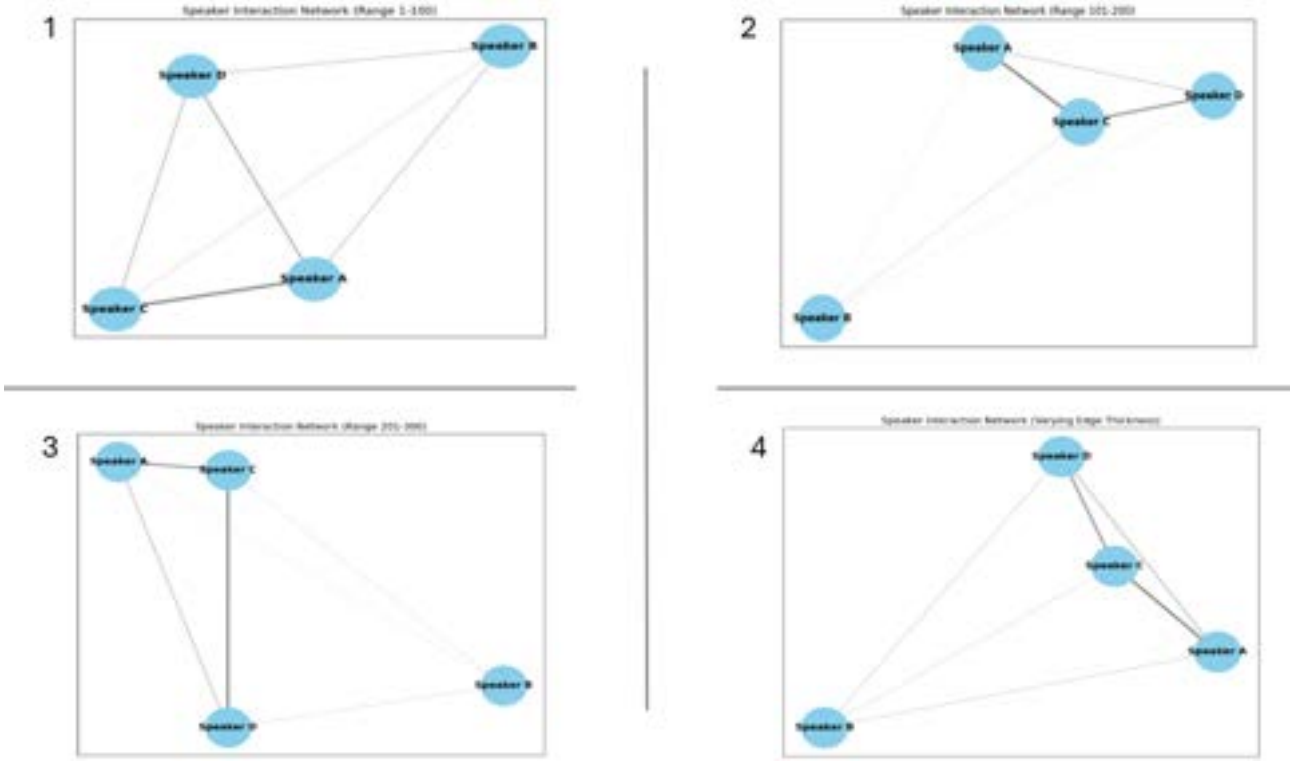
Table 2. Speech transition occurrences between group members.

Rank	Speaking direction	Frequency	Rank	Speaking direction	Frequency
1	'Speaker A' → 'Speaker C'	70	7	'Speaker A' → 'Speaker B'	8
2	'Speaker C' → 'Speaker A'	66	8	'Speaker B' → 'Speaker D'	8
3	'Speaker C' → 'Speaker D'	50	9	'Speaker D' → 'Speaker B'	5
4	'Speaker D' → 'Speaker C'	45	10	'Speaker B' → 'Speaker C'	5
5	'Speaker D' → 'Speaker A'	22	11	'Speaker B' → 'Speaker A'	3
6	'Speaker A' → 'Speaker D'	14	12	'Speaker C' → 'Speaker B'	3

Network Structure And Temporal Dynamics

Figure 1 illustrates interaction networks derived from SNA, where node proximity reflects interaction strength and edge thickness represents transition frequency. To examine temporal changes in participation patterns, the interaction data were segmented into three consecutive phases of 100 speech occurrences, followed by an aggregated network representing all 300 transitions.

Figure 1. Temporal changes in interaction patterns among four participants based on SNA results.



During the first phase, interactions were relatively balanced, although Speakers A and C were already more strongly connected than other pairs. In the second phase, Speaker C became increasingly central in the network, while Speaker B engaged less frequently and moved farther from the core interaction structure. This pattern intensified in the third phase, with Speakers C and A forming even stronger ties. The aggregated network highlights Speaker C's dominant role in the discussion and Speaker B's consistently peripheral position.

Overall, these results demonstrate that SNA effectively captures participation patterns and reveals

distinct student roles within science group work. By integrating transition frequency, speaking duration, and network structure over time, SNA enabled the identification of central and peripheral participants, providing clear evidence in support of RQ2.

RQ3. How Are Gender, Science Identity, And Personality Traits (Extroversion) Related To Students' Participation Patterns And Roles In Science Group Activities?

To further explore how individual characteristics relate to participation patterns and roles, each speech occurrence was manually coded into one of six functional categories. This analysis complemented the SNA results by examining not only how much students participated, but also how they contributed to the ongoing discussion.

Among the six categories, cumulative elaboration statements were first examined to trace how participants contributed to advancing the discussion over time. As shown in Figure 2, the two male students exhibited a crossing pattern in cumulative elaboration, indicating that they alternated in taking the lead during the conversation. In contrast, Speaker B (Female 1, low science identity, introverted) contributed to elaboration primarily during the early phase of the session but gradually withdrew from active participation around the midpoint. Speaker D (Female 2, average science identity, extroverted) showed a gradual increase in elaboration contributions over time; however, her participation followed a different trajectory from that of the male students and did not converge with the dominant interaction pattern.

Figure 2. Cumulative elaboration statements over time.

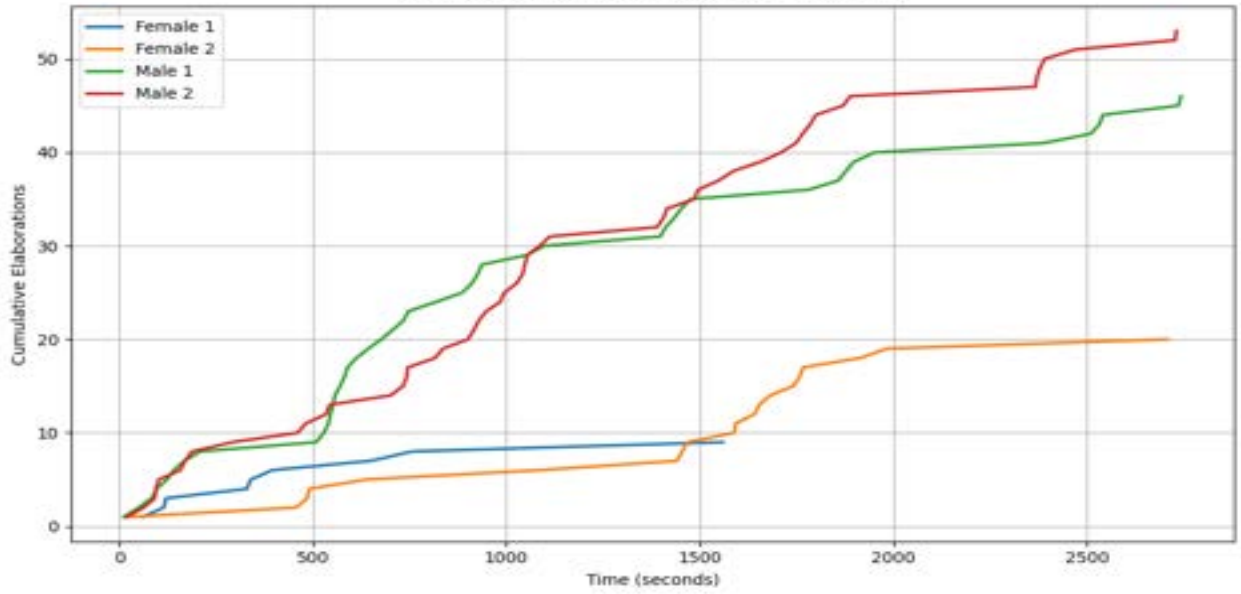
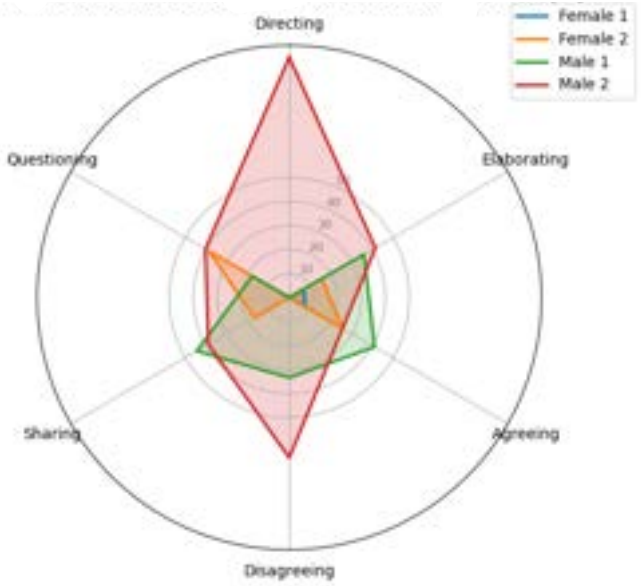


Figure 3 presents the proportion of speech functions attributed to each speaker. Speaker C (Male 2, average science identity, extroverted) dominated across multiple conversational functions, including directing, elaborating, and disagreeing, indicating a central and influential role in shaping the discussion. Speaker A (Male 1, high science identity, extroverted) contributed primarily through elaboration, suggesting a supportive but still central role. In contrast, Speaker B (Female 1, low science identity, introverted) accounted for a substantially smaller proportion of all speech categories, reflecting a marginalized participation role. Speaker D (Female 2, average science identity, extroverted) contributed across several categories but was less involved in directing or disagreeing, functioning primarily as an active follower within the group interaction.

Taken together, these findings suggest that participation patterns and roles in science group work are shaped by an interplay of gender, science identity, and personality traits. In this group, male students—regardless of differences in science identity—occupied more central and directive

roles, while female students displayed more varied participation trajectories that were sensitive to both science identity and extroversion. Although exploratory in nature, these results provide initial evidence that individual characteristics are meaningfully related to how students participate and position themselves within science group activities, addressing RQ3.

Figure 3. Proportion of each category attributed to speakers (%).



Discussion

Building on the results addressing RQ1, the ASR system demonstrated performance that exceeded commonly reported feasibility thresholds for classroom-based, multi-speaker environments (Wang et al., 2024; Attia et al., 2024). This high level of performance can be attributed not only to recent advances in ASR technology but also to the use of individual microphones with separate-channel recording, which substantially improved speaker separation and audio quality. Together, these results provide empirical evidence that ASR, when supported by individual microphone systems, can be successfully applied to investigate student interactions in authentic, co-located classroom activities involving more than 16 students.

In addition, whereas previous studies have primarily focused on online learning contexts (Saqr et al., 2018; 2020), the integration of SNA in the present study proved effective for identifying participation patterns and distinguishing central and peripheral roles within authentic, face-to-face science group work (RQ2). By modelling interaction structures over time, SNA made visible participation dynamics that are difficult to capture through traditional observational approaches alone. When combined with functional analyses of student talk, the results further revealed how participation roles are shaped by a complex interplay of gender, science identity, and personality traits such as extroversion (RQ3). These findings underscore the importance of considering individual characteristics when examining collaborative learning processes in science education.

While the present study is exploratory in nature and based on a limited number of groups, it demonstrates the methodological promise of combining ASR and SNA for scalable and fine-grained analyses of classroom interaction. Accordingly, future work should further validate the use of ASR and SNA in educational research and deepen understanding of equitable participation and inclusion in science classrooms with larger student populations.

Acknowledgement

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Unpacking Science Teachers' Discursive Practices In Instructional Modelling.

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This study explores the discursive practices of science teachers in modelling-oriented teaching contexts, particularly emphasising dialogic classroom decision-making and its impact on students' learning opportunities. Teachers' speech turns are analysed when implementing a task with modelling potential to visualise these discursive processes. This is achieved through a discourse analysis of the productive conversation, including the breakdown of the dialogue into modelling phases (familiarisation, discussion, and consensus) and the classification of interaction types such as validation, information, clarification, challenge, and consolidation. The unpacking of these modelling-oriented talk moves highlights how teachers perceive and respond to student responses and how their discourse can facilitate or hinder the modelling process. The results suggest that the talk moves teachers use to enable the development of a productive conversation in which students' cognitive engagement in modelling processes is promoted.

Keywords: Instructional Modelling, Talk Moves, Teachers' Discursive Practices

Theoretical Framework

In accordance with the needs of the learning process in science education is critical for teachers to promote interactive talk in the classroom, as questioning students increases students' motivation to learn, supports productive classroom discussion, and fosters knowledge construction (Tiffany et al., 2023; Tytler & Aranda, 2015). Questioning is a process of collaborative learning that requires active, reciprocal participation that promotes a tension between students' need to express their ideas and teachers' need to mediate their reasoning in terms of scientific knowledge (Hamnell-Pamment, 2023). In modelling-based instruction, this tension is palpable in the mediation process teachers enact to facilitate students' mental model-building. As a teaching approach, modelling instruction requires teachers to promote an instructional task sequence that allows students to engage in modelling practices (Garrido & Couso, 2024). This performance is associated with a student-centred discourse, where teachers encourage students to express their ideas and promote divergence and convergence to help them gradually revise and refine their initial models.

Promoting the performance of modelling practices through dialogic teaching involves spaces to listen to other ideas, reasoning with others, and negotiating new ideas (Vergara et al., 2025b). So far, the study of the dialogic opportunities given in science instruction has been focused in the count of instances in which discursive strategies are used (Christodoulou & Osborne, 2014), the comparison of the distribution of linguistic movements in the dialogue (Balyan et al., 2022), the presentation of dialogue in a particular episode (Cui & Teo, 2023), the time spent on the stages of a task (Newman, 2017), flow diagrams (Larusso et al., 2023), and the use of discursive categories over time (Tytler & Aranda, 2015). In science modelling processes, visualisations have focused on the flow of the chain of discursive strategies (Vergara-Sandoval et al., 2025a) and graphs of discourse variation in different episodes (Garrido Espeja, 2016). However, to understand how teachers promote modelling practices, a deeper analysis of their dialogical decisions is required.

Exploring productive conversations between teachers and students through conversation analysis can shed light on teachers' discursive strategies to facilitate model construction (Hamnell-

Pamment, 2023). While embedded within the intricate, in-the-moment decision-making processes of teaching, these strategies can be identified and visualised. To achieve this, it is essential to analyse teachers' talk moves in terms of their specific purposes. This approach also highlights the importance of examining the balance between allowing students to articulate their reasoning and the teacher's role in guiding instructional modelling (Hamnell-Pamment, 2023).

Analysing teacher discourse in dialogical science classrooms can reveal patterns and strategies that contribute to refining students' ideas as they develop a school scientific model (SSM). However, the learning opportunities available depend significantly on how tasks are implemented (Krist et al., 2023). Given that task implementation can often diminish a task's modelling potential, it becomes crucial to integrate an analysis of teachers' discursive practices that foster students' intellectual engagement (Tekkumru-Kisa et al., 2023). Although efforts have been made to enhance students' epistemic agency (Krist et al., 2023), the role of teachers' discursive decisions in shaping discussions within the specific context of task implementation has not been extensively explored.

Therefore, it is important to identify how talk moves within a modelling process mediates students' learning (Tytler & Aranda, 2015), particularly when considering how these moves are shaped by teachers' noticing, interpretation, and responses during task implementation and student interactions. This research aims to examine visualisations of classroom interactions between teachers and students by analysing modelling-oriented talk moves and their patterns, with a focus on decisions that support students' modelling processes. By characterising these talk moves, the study seeks to illustrate the learning opportunities created by science teachers through their modelling-oriented discourse.

Research Question

In characterising classroom interactions between teachers and their students in which dialogic decision-making affects learning opportunities in a task with modelling potential, we seek to respond to the following research question:

> RQ: What discursive decisions do science teachers make to facilitate modelling processes in their students?

Methods & Context

To achieve the study's objective, a qualitative research approach with discourse analysis was employed. The study involved 3 Chilean chemistry teachers, Chris, Marina, and Caroline, who constitute the participants of this research. The data collection included the audiovisual recording of one lesson for each secondary education teacher.

Context Of The Study

The teachers in this study are part of a learning community in model-based teaching. The learning community lasted a year and a half, during which they revised their ideas about models and modelling, discussed their experiences, and received feedback on the tasks with modelling potential that they enacted in their classrooms. In this context, in the last months of the learning community, the teachers co-designed a modelling-oriented teaching and learning sequence (TLS) that follows the criteria for a modelling-oriented task proposed by Cortés-Morales & Marzabal (2025a) and the design principles for a modelling-oriented TLS proposed by Tena & Couso (2023).

To recognise teachers' discursive practices and establish possible talk move patterns in the modelling conversations, the implementation of task 5 was selected for its characterisation: "Represent and describe the final state of the reaction". This task is part of an experiment that

compares the reaction between copper sulphate and iron shavings in a TLS about ponderal laws.

By presenting a scientific phenomenological context associated with low cognitive demand in an open-ended question, it can be established that the tasks have low modelling potential (Cortés-Morales & Marzabal, 2025a). This low potential is related to a selected context that is distant from the students' experiences and knowledge, so an extensive familiarisation process may be required to enable students to relate what they know about the phenomenon.

Strategies For Data Collection And Analysis

The video recordings were made following the analytical strategy proposed by Lehesvuori et al. (2018) to analyse teaching processes. This meant using a camera positioned at the back of the classroom to record the teacher's interactions with the whole group and a mobile camera to record the teacher's interactions with the small groups. This meant that a camera and microphone followed the teacher to record the conversations.

A coding scheme was developed to examine the talk moves used by science teachers to support their students' modelling; the analysis required arranging the codes to visualize the discourse. Previous work on modelling conversations made by Tytler & Aranda (2015) and Vergara-Sandoval et al. (2025a) led the researchers to make adaptations in their proposals in order to consider how the nature of the talk move could change the purpose of the discourse action taken by the teachers. Consequently, this tool for characterising conversations considers the purpose of the talk move and its nature depending on how the move is framed. In this sense, a distinction was made between the cognitive demand imposed by the teacher and whether that demand entails a process of requesting or providing ideas for constructing an SSM (Table 1).

The dialogue between teacher and students during a task with modelling potential was coded according to the following aspects of discourse:

a) Communicative act. The identification of turns of speech, differentiating between student and teacher turns, and communicative intentions to differentiate one turn among several together (Hennessy et al., 2016)

b) Typology: The distinction between productive conversation and general classroom conversation (Soysal, 2019)

c) Organisation: The organisational difference between students in conversation, i.e., interaction with the teacher in a small or large group (Alexander, 2018).

d) Identification of the phase of the modelling cycle that teachers promote with their discourse: familiarisation, discussion, and consensus (Garrido & Couso, 2024).

e) Characterisation of the type of interactions in Table 1 (next page).

This qualitative research proposes analysing data to visualise the discourse led by teachers through their turns of speech (Category A), which are framed by the organisation of the students with whom they interact (Category C) in a phase of the modelling cycle (Category D). These turns are differentiated by the type of conversation (Category B) and the type of interaction the teacher promotes (Category E).

For this, in the first instance, how teachers interact with their students during the same task was characterised and presented in the visualisations by their location on the axis. In a second instance, the purpose of the interactions was characterised by the sub-code indicated in the turn-of-speech box (P: Provide; R: Request). The discourse display is a chronological map of the teacher's talk moves as they implement a common task.

Table 1. Talk moves for modelling conversation (Cortés-Morales et al., 2026).

Talk move	Teacher request…	Teacher provides…
Acknowledge		A word or phrase to signify the value of the student's contribution, to validate or acknowledge a point of view, or time for students to think about what they have expressed. *i.e., ok, very good, right*
Inform	Information to get a first appreciation of the students' ideas *i.e., How are we doing? What happened? What were you able to observe?*	
Clarify	Students to expand on their ideas with a more robust response or to explain what they meant. *i.e., You say it's an oxidation, what was oxidized? And that, to what equate? Ok, we would see particles, particles of what?*	A thought-provoking idea by providing information or an analogy for the revision of an idea about the phenomenon. *i.e., But if it were to dye it blue and we don't see it blue, then maybe the change doesn't go hand in hand with dying it*
Challenge	Students to check the ideas that have been put forward or ask for an interpretation that helps to contrast ideas to elicit an idea when something doesn't fit. *i.e., ok, it melts [repeating student's answer] how so?*	A questioning of the students' ideas and rationales about the phenomenon. *i.e., Do we have the same results if we have different amounts of copper sulphate?*
Consolidate	Students to integrate the ideas discussed into a single answer. *i.e. [To end the task] Is it the same if we have two volumes of copper sulphate in the reaction?*	A synthesis of the students' ideas in a single answer. *i.e., That is also relevant because when I have a chemical change, the changes are important; besides the change in color, we also see a change in temperature.*

Findings

The analysis of teachers' discourse employs visualisations that allow us to observe how discourse and talk moves are structured in a productive conversation for a task with low modelling potential. This first finding yields a methodological tool that enables us to observe the rhythm and consistency of the dialogue in a modelling-oriented classroom. These discourse visualisations (Figure 1) show, on the left, the modelling-oriented talk moves, and, on the right, their uses by a teacher in chronological order. On top, we can examine if the conversation is between the teacher and the whole group (WC), or with a particular small group (G. number). Below the class organisation, we will find the modelling phase that the teachers promote in their discourse, colour-coded: cyan for familiarisation, blue for discussion, and purple for consensus. The descriptions of the expected conversations for each modelling phase follow the studies by Garrido

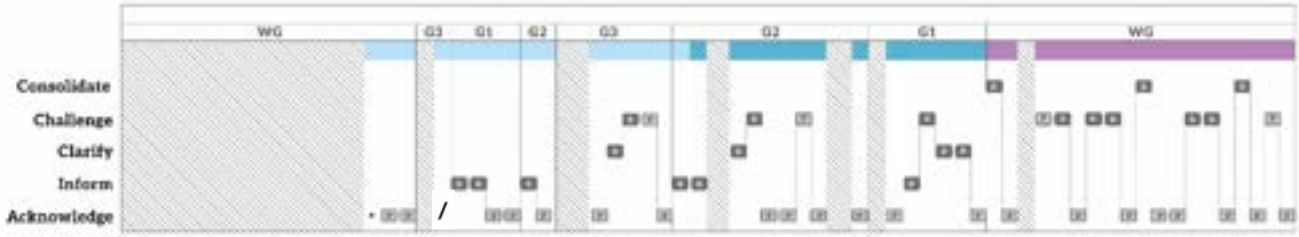
& Couso (2024) and Cortés & Marzabal (2025b). In a familiarisation phase, the teachers approach a contextualised problem situation and expect students to recognise that they need a model, express it, and, in their conversations with others, understand that there can be different versions of the model in the classroom. In the discussion phase, teachers ask questions to help students use their ideas iteratively, testing and contrasting them to revise their initial model. In the consensus phase, teachers facilitate a dialogue in which students agree on a final model that emerges from collective understanding.

In the case of the turn-of-speech boxes, we can identify whether the teacher is requesting (R) or providing (P) an idea in the modelling-oriented talk move. They have been coloured as well to facilitate the reading of the visualisation, light grey is providing, and dark grey is requesting.

Finally, every conversation that is not dialogic and interactive as a communicative act (Mortimer & Scott, 2003) is levelled with general classroom conversations and appears in the visualisation as diagonal shading. Every speech turn in a teacher's general classroom conversation has the same width as the turn-of-speech boxes with the talk moves.

In addition to the codes typified in the visualisation, two icons have been used to show how the tasks are presented to students. The asterisk (*) marks the teacher reading the task, in some tasks teachers take a time before reading the task to talk with students about something that they need to be able to complete the task, in such cases as in figure 1, we can see that the task does not start with the reading of the task, but with an explanation about how to use a balance. Another icon is a slash (/) that indicates turns of speech in which the teacher repeats the task with some alteration, providing a reformulation or simplification of the task instructions to the students.

Figure 1. Visualisation of Marina's talk moves in the task.



Science Teachers' Discursive Practices In Instructional Modelling

The analysis of the visualisation for the three chemistry teachers allows us to examine how the productive conversations unfold in instructional modelling. The findings show patterns of the dialogue that promote students' revision of their SSM.

Firstly, most of the speech turns relate to productive conversations. Although most of the modelling conversations are productive conversations, some of them are general classroom conversations that provide students with the learning opportunities they need to refine their initial model. This means that, in implementing tasks with modelling potential, an alternation between productive and general classroom conversations is required. This shift between communicative acts reflects teachers noticing and acting in accordance with the ideas expressed by their students, a key aspect of modelling conversation, as well as the responsiveness of teachers in the dialogue they mediate.

Similarly, teachers' dialogue involves extensive conversations that promote students' familiarity with the phenomena, accounting for 100% of Caroline's dialogue, 46% of Marina's turns, and 18% of Chris's dialogue. Chris's turns of speech in the familiarisation phase, unlike Marina's and Caroline's, are not grouped together, as each conversation with the small groups starts with familiarisation, shortening the amount of talk moves used in this phase. However, there is a consistency in the phase for this low modelling potential task, which relates to the request for

information each time the teachers start a familiarisation dialogue with the small groups.

Secondly, the use of talk moves oriented towards modelling shows that most of the moves have a nature of requiring (R) students' ideas in different patterns. On the one hand, teachers ask for clarification, followed by a challenge to their ideas when they are ending a familiarisation phase or starting a discussion phase. On the other hand, teachers ask them to challenge their ideas, then require clarification during the discussion phase. In the latter, teachers expect students to be clear about their ideas and how they differ from their initial model.

Lastly, there is constant use of validation moves, which are the most used talk moves. Teachers use validation moves in every phase, with every small group, and with the whole group, and they alternate them with other modelling-oriented talk moves. These moves account for 45%, 42% and 20% of the modelling-oriented talk moves used by Marina, Chris, and Caroline, respectively. The repeated use of these moves relates to teachers giving students the opportunity to see their ideas as valid, as a starting point, or as a way to explain the phenomena. They are a transitional move that teachers put in place to motivate students during the process and keep the dialogue going. Even though their use does not promote modelling practice, it allows it to unfold.

Discussion & Implications

The findings in this study lead us to believe that, when implementing the task, the teachers can maintain a productive conversation oriented toward an instructional modelling process that goes beyond the modelling potential. In this sense, Chris, Marina, and Caroline decide to facilitate the modelling process for their students by introducing a recurrent familiarisation phase into whole- and small-group conversations.

As the potential depends on the practice to be developed, in which the description (demand of the task) could lead the teacher to close the conversation in search of a particular description that teachers expect from the students, we can see in Marina's and Chris's cases that the modelling potential increases as the teacher is inviting students to reason out the observations that lead them to a representation or description of the phenomena (Park et al., 2021) instead of searching for a particular answer.

Consequently, regarding the management of modelling processes, the teachers can involve students in productive discussions. The actions of the observed science teacher are fruitful in engaging students in modelling processes. Nevertheless, the same could not be said of Caroline's productive conversations, as she closed the dialogue, ending the task before the conversation reached the discussion phase of the modelling process.

The shifts between productive and general classroom conversations are not interruptions, but rather a key discursive strategy that teachers use to respond to students' emergent needs during modelling. In the same way, each teacher exhibits common patterns but a particular style in managing classroom dialogue, demonstrating a responsive and adaptive mediation that supports transitions between phases of the modelling process, depending on the group they are talking with and the task context. The discourse decisions teachers make to manage and promote the continuation of a conversation relate to understanding when a general classroom conversation will help students in the development of the modelling phase, choosing when validation will secure students expressing their initial representations and when a particular pattern of talk moves will be more appropriate to help them review their model and negotiate the personal ideas in a group setting.

The analysis of the results suggests that mapping these interactions could serve as an analytical tool for discussing and improving teachers' discursive practices, thereby optimising students'

intellectual engagement in modelling processes.

Disclosure. It should be noted that part of this proceeding was published in an article in Spanish that can be found at https://orcid.org/0000-0002-3804-7942

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Part 8 / Strand 8

Scientific Literacy And Socio-scientific Issues

Co-editors: *Isabel María Cruz Lorite & Eliza Rybska*

Part 8 / Strand 8 Scientific Literacy And Socio-scientific Issues

Teaching and learning about scientific literacy, socio-scientific issues and citizenship education. Topics in the strand include understanding the social aspects of science, critical media/literacy reasoning, decision making and debates on socio-scientific issues (SSI), public engagement and participation in science and understanding the relevance of science. The aforementioned topics can focus either on teachers or students.

Sub-themes:

1) Teaching and Learning about Scientific Literacy
2) Engaging Students in Socio-scientific Issues (SSI)
3) Critical Media Literacy in Science Education
4) Public Engagement and Participation in Science

Contents

Strand 8: Scientific Literacy And Socio-scientific Issues 635
Manipulation Of Illustrations And Graphs In Chemistry Education 638
How Do Greek Students And Teachers Perceive Climate Change? 645
How Physics Teachers Think About Science – Physics Teachers' Views Of Science Compared To Researchers' Views 651
Fighting Fake News In Science Project: An Action Research Study Involving Brazilian Students, Teachers And Academics 659
Pre-service Primary Teachers Evaluate Media Sources On Climate Change 665
The Deep Structure for Teaching and Learning Socioscientific Issues 672
Socioscientific Issues And Laboratory Work In Lower Secondary School - Some Challenges 680
Argument Development Through Socioscientific Issue-Based Teaching: Asteroid Mining With Gifted Students 685
Connecting The Dots: Quassr Scores And S^3R Profiles In Preservice Teachers' Socio-Scientific Scenarios 692
Unlocking Perspectives: Exploring Initial Design Principles Of Culture-Based Socio-Scientific Issues Training For Indonesian Pre-Service Biology Teachers 699
Science Education And Communication: Innovative Methods To Promote Scientific Literacy 704
Understanding AI In Secondary School Education: How Technical Knowledge Affects Students' Technology-Critical Understanding 710

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Strand 8: Scientific Literacy And Socio-scientific Issues

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The chapter "*Scientific Literacy and Socio-scientific Issues*" brings together contributions that tackle a significant challenge in today's science education: preparing learners and teachers to engage critically, responsibly, and thoughtfully with science in a complex and unpredictable world. Socio-scientific issues (SSI) have received more attention over the past twenty years because many problems facing modern societies—like climate change, loss of biodiversity, artificial intelligence, genetic technologies, food security, public health crises, and sustainability transitions—cannot be understood or solved with scientific knowledge alone (Sadler, 2004; Zeidler et al., 2005; Levinson, 2018). These issues involve uncertainty, different perspectives, competing values, and the necessity of making choices despite incomplete information. Citizens need to engage not only with scientific facts but also with ethical, cultural, economic, and political factors. The growing importance of SSI is especially clear in what is often called a post-truth era. Here, scientific information competes with misinformation, disinformation, ideological narratives, and content shaped by algorithms circulating in digital media (Lewandowsky et al., 2017; Erduran, 2025). As a result, scientific literacy has become both more crucial and harder to achieve. Modern scientific literacy goes beyond knowing scientific concepts and procedures. It includes the ability to evaluate evidence, assess the credibility of sources, recognize uncertainty, understand how scientific knowledge is created and shared, and engage meaningfully in public discussions and decision-making processes (OECD, 2019; National Academies of Sciences, Engineering, and Medicine, 2016). In this context, socio-scientific issues have been increasingly recognised as a powerful educational approach for preparing learners for responsible citizenship, as they engage students in considering the relevance of science in societal decision-making and encourage them to evaluate scientific, ethical, political, and cultural dimensions of contemporary problems (Evagorou & Dillon, 2020).

Developing such capacities is not only a challenge for students but also for teachers, researchers, educational institutions, policymakers, and society as a whole. A major factor driving these changes is the fast rise of artificial intelligence. AI has entered everyday life, workplaces, education, research, and public discussions at an unmatched speed. Technologies like machine learning, recommender systems, generative AI, and large language models have changed how information is produced, shared, and consumed. While these advancements provide new chances for learning and scientific communication, they also raise significant questions about transparency, ethics, data privacy, bias, accountability, and the reliability of information (Long & Magerko, 2020; Ng et al., 2021). Therefore, learners today need not just digital skills but also a critical perspective on technology, helping them understand and assess the social effects of new technologies. From an education standpoint, these fast changes call for new skills and new forms of literacy. People increasingly need to make decisions on issues with uncertain, long-term, and hard-to-predict consequences. Students, teachers, researchers, policymakers, and communities often face questions without clear or universally accepted answers. Choices about climate action, biotechnology, public health measures, sustainability, or regulating AI often have to be made before all relevant evidence is available and without certainty about future outcomes. Thus,

preparing learners to handle this uncertainty is a key goal of science education (Funtowicz & Ravetz, 1993; Levinson et al., 2017).

In this context, the contributions in this chapter provide valuable insights into fostering scientific literacy and engagement with socio-scientific issues across various educational settings. A strong theme throughout the chapter is the connection between scientific literacy and the fast-changing digital world. Several studies examine how learners understand artificial intelligence, machine learning, social media, and science communication, highlighting both the opportunities and challenges these environments present for developing critical tech and media perspectives. Issues of misinformation, source evaluation, trust in science, and the responsible use of digital technologies emerge as key concerns for science education in the twenty-first century.

Another major focus is socio-scientific reasoning and argumentation. The contributions investigate how students and future teachers think through complex and controversial topics like sustainability, climate change, resource use, biotechnology, and emerging technologies. They explore the development of argumentation, critical thinking, moral reasoning, and decision-making. They show that meaningful engagement with socio-scientific issues requires learners to connect scientific knowledge with ethical, cultural, economic, and societal factors.

The chapter also emphasizes the essential role of teacher education. Several studies analyse how future teachers gain the knowledge and skills needed to promote SSI-based learning. They pay particular attention to culturally responsive teaching, sustainability reasoning, and designing learning environments that help students relate scientific knowledge to their own experiences and cultural backgrounds. These contributions acknowledge that teachers are not just sources of knowledge but also key guides who assist students in navigating uncertainty, evaluating competing claims, and engaging in informed and responsible decision-making.

Overall, the studies in this chapter show that scientific literacy today is closely linked to the ability to engage with socio-scientific issues. They stress the need for educational approaches that encourage critical inquiry, ethical thinking, evidence-based reasoning, and active participation in democratic societies. By doing this, the chapter supports ongoing efforts to rethink science education for a world marked by rapid technological change, global connections, and increasing uncertainty.

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Manipulation Of Illustrations And Graphs In Chemistry Education

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Challenges like manipulation and misinformation are of particular importance in the context of modern types of media due to the absence of classical gatekeeping mechanisms. Especially illustrations and graphs with a scientific background can be manipulated in various forms. Due to the influence manipulation strategies can potentially have on society, the promotion of competencies enabling individuals to detect manipulation is needed. Therefore, a teaching unit that deals with the analysis of illustrations and graphs in chemistry education and the detection of manipulation strategies used in media content was created. In the four lessons, the students became familiar with different strategies and aims of manipulators. The media content of the teaching unit is embedded in a chemical or scientific context, and the illustrations are adapted to the design of known social media platforms. The exploratory evaluation of the unit included open-ended questions and a Likert-type questionnaire. It was investigated to which extent the students can describe the manipulation strategies used in specific illustrations and graphs at the end of the unit. The results of the evaluation show that the students are able to describe manipulation strategies used in exemplary media content by utilizing vocabularies resembling the manipulation strategies learnt in class. However, the majority is not able to identify all the different strategies. Consequently, the teaching unit seems to be able to partly promote Scientific Media Literacy, but additional practice and the acquisition of a routine is needed.

Keywords: Case Studies, Classroom Practices, Scientific Literacy

Theoretical Background

Relevance

Due to the increasing digitalization and its challenges, the promotion of media literacy became relevant as an educational and macro-social intersectional issue in Germany (KMK, 2017) and worldwide (UNESCO, 2021). Therefore, it is being integrated into different subjects. Media literacy is also important for the everyday life of young people as they regularly get confronted with media content – that often has a scientific background – and also have to deal with digital media's challenges. However, regular interaction with such content does not always mean that the interaction is reflected by users, and challenges like manipulation and misinformation occur frequently in digital media (Barzilai & Chinn, 2020; Kammerl, 2014; Tulodziecki et al., 2021). But without a deepened reflection of the content, the influence of manipulation and misinformation grows. In particular, illustrations are the aim of manipulation, because pictures taken by a camera are often associated with higher evidence (Schicha, 2005; Stein et al., 2020). Misleading graphs play a major role in advertising in order to present the product in an appealing light (Danciu, 2014).

Manipulation Strategies

Connected to manipulation, media content can be rapidly altered through strategies such as the choice of colours or changes in context created by accompanying text (Danciu, 2014; Schicha, 2005). Graphs, which are frequently used in advertisements, are also susceptible to manipulation in various ways (Danciu, 2014), for example through colour choices or by adjusting the axis range (Schaffer, 2020; Walla, 2008). This shows that manipulating media content is not particularly

complicated, which is why it is an important issue that needs to be addressed in the context of increasing digitalization. Furthermore, the media is able to influence the public perception of different issues, for example by using manipulation strategies. With regard to chemistry, the consumption of manipulated content can evoke, for instance, aversions and fears (Rollini et al., 2022). This phenomenon of creating irrational fears towards chemistry and chemicals is known as chemophobia (Rollini et al., 2022). However, the opposite can also be achieved by using manipulation strategies that suggest seriousness and scientific credibility even in areas where these are absent (Höttecke & Allchin, 2020). Additionally, the media can change the perception of scientific debates (Lewandowsky et al., 2019). Taken together, these aspects complicate interaction with digital media, particularly social media, when individuals seek to engage deeply with content. Consequently, educational contexts must foster competencies that enable learners to address these challenges effectively.

Application To Education

In order to overcome the challenges of digital media in a responsible manner, a reflected interaction with content is needed, especially when it comes to science-based information (Chang Rundgren & Rundgren, 2014). Illustrations and graphs with a scientific background are examples which can often be found in the digital media and can be manipulated in different ways, particularly on social media platforms due to the absence of traditional gatekeeping mechanisms (Höttecke & Allchin, 2020). In an educational context, a mainly preventive approach is needed, supporting students to deal with manipulated media content in the future (van der Linden, 2022). Teaching units dealing with topics like manipulation are important to promote students' critical interaction with digital media and the scientific information in it.

In the case of science-based media content, the concept of Scientific Media Literacy describes the skills and knowledge needed to deal with it (Chang Rundgren & Rundgren, 2014). The concept combines the fields of Scientific Literacy and Media Literacy and can be integrated and promoted in the science classroom (Chang Rundgren & Rundgren, 2014).

Development Of The Teaching Unit

Based on the described challenges, the aim of this exploratory study was to develop and evaluate a teaching unit of four school lessons on the topic of manipulation of illustrations and graphs in chemistry education and to (at least partly) promote Scientific Media Literacy. It has been investigated to which extent the students are able to describe the manipulation strategies used in specific illustrations and graphs at the end of the unit. The target group were German students in grades 9 to 11, and the focus of the lessons was on the analysis of different science- and chemistry-based illustrations and graphs. In addition, the students evaluated different media contents in different exercises and created their own manipulated illustrations to change their perspective. They became familiar with various manipulation strategies and how to detect them. The scientific backgrounds of the media content were chosen to be controversial. Topics like cosmetics, glyphosate, clean and natural beauty, nutritional supplements, plastics, and energy supply were part of the teaching unit. All the images were created using the software Canva based on a prior analysis of existing social media posts to allow a clear focus on the manipulation strategies and decrease distraction. An example of such manipulated media content can be seen in Figure 1.

Figure 1. Exemplary illustration of the teaching unit about glyphosate.



Detailed prior knowledge about the topics was not needed to answer the different tasks. For exercises which supposed a more comprehensive knowledge about the specific issue, information texts were created to support the students.

Methods

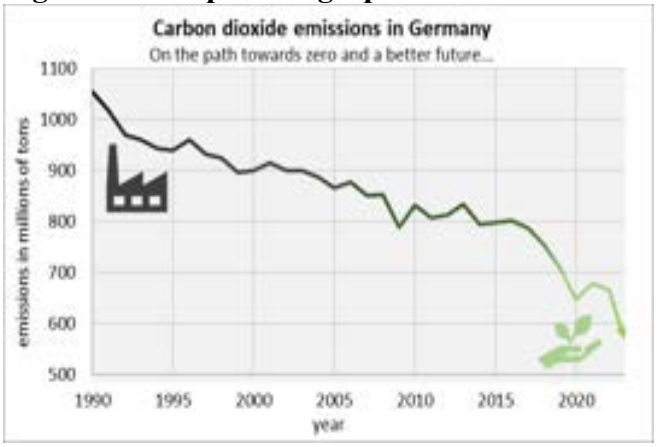
To investigate the impact of the unit on the students a mainly qualitative approach was used, which consisted of a participant observation and an evaluation sheet which combined open-ended and Likert-typed questions as well as two exercises in which the students had to describe the manipulation strategies used in two exemplary media contents (Figure 2, 3) and questions including feedback on the teaching unit. The unit was implemented and evaluated in a group of 53 students from grades 9 to 11. The participant observation was used to improve the identification of difficulties that occurred during the lessons, while the main part of the evaluation consisted of the evaluation sheet.

The media content used in the exercises of the evaluation sheet can be seen in Figures 2 and 3, each of them has been manipulated by applying several strategies. The students were not familiar with these specific examples and therefore had to apply the strategies they have learnt in their descriptions. Figure 2 has been manipulated by the choice of colours, added image elements such as plants and laboratory equipment, the proportions of the different parts of the figure, and the accompanying text (Schicha, 2005; Stein et al., 2020). Especially the percentage of visible moisture increase without context and information about the origin is misleading (Danciu, 2014). The manipulation strategies of Figure 3 consist of the choice of colours, unnecessary details such as the arrow at the end of the curve and the two symbols, the accompanying text, and the changed axis range (Schaffer, 2020; Schicha, 2005; Walla, 2008).

Figure 2. Manipulated illustration from the evaluation.



Figure 3. Manipulated graph from the evaluation **(source of data: Umweltbundesamt, 2023).**



The additional feedback on the teaching unit included aspects like the interest in the topic, the quality of the unit, and the self-assessment of the students' own learning gains. To obtain answers on these aspects, Likert-typed questions, open-ended questions, and a self-assessment of the individual learning gains on a scale from one to ten were used.

After the editing of the evaluation, the open-ended questions of the evaluation sheet were analysed using qualitative content analysis (Kuckartz & Rädiker, 2022) and for the Likert-typed questions we used descriptive statistics due to the exploratory nature of the study. Categories were formed based on the students' descriptions (Kuckartz & Rädiker, 2022) and afterwards compared with the manipulation strategies from the lessons described above. In addition, mean values and standard deviations of the Likert-items and the self-assessment of the individual learning gains were calculated.

Results

Description Of Manipulation Strategies

The results of the exercises show that most of the students are able to describe the manipulation strategies used in illustrations and graphs at the end of the teaching unit. Therefore, they are able to recognize manipulated media content. To describe the manipulation strategies, the students mainly used the vocabularies learnt in class. However, in most cases the students are not able to identify all the strategies from the two examples (Figure 2, 3).

Especially manipulation strategies like the choice of colours or the influence of the context, which has been changed by the text of the media content, are often detected by students. These strategies occur in both types of media and were therefore repeatedly addressed in the unit. When describing Figure 2, the majority of students refer to the text containing the percentage. The visual elements that establish a connection to nature and chemistry, such as the plants and laboratory equipment, were also often recognized. References to nature are mentioned by more than the half of participants.

It was discovered that the analysis of the graph seems to be more difficult for some students than the analysis of the illustration. The most frequently mentioned category is the choice of colours within the graph of Figure 3. The two symbols are also often described as manipulative. Manipulation strategies associated with mathematics, such as the changed axis range in Figure 3, were described less frequently and therefore seem to be more difficult for most of the students to detect. Here, the difficulty seems to be that the students have to learn how to read a graph at first (Schaffer, 2020). After that, they gain a basis to learn how to detect the manipulation of the graph

more in detail. To minimize the difficulties with graphs, general competencies for the interaction with them are needed in different subjects such as mathematics and the sciences.

The descriptions of manipulation strategies in illustrations and the results of year 11 are more comprehensive than in years 9 and 10. On average, older students describe more strategies in their descriptions, which goes in line with research findings on consumer socialization (John, 1999). Nevertheless, most students in all grades can identify at least one strategy, which means that they are aware that manipulation is present. In addition, it is noticeable that some students have begun to interpret the effects and intentions of the strategies. This was not expected in both tasks.

Feedback

Self-Assessment Of Learning Gains

In addition, the students rate their own learning gains as rather high than low, with an average of 6.43 out of 10. The average of year 11 is the highest with 6.76, and the average of year 9 the lowest with 6.06. The standard deviation is particularly high in the ninth grade, which shows that differences within the learning group exist. While two students even reported learning gains of 10, another student of the same class reported a gain of 1. The result of the self-assessed learning gains as a whole could relate to the self-assessment of a higher previous knowledge and the fact that the teaching unit mainly promotes skills and less factual knowledge. In the ninth grade, general differences in performance within the learning group may also have been an influencing factor.

Open-Ended Questions

Overall, the feedback concerning the interest in the topic, the learning gains and the whole unit is quite positive. Many positive aspects like the creation of an own manipulated illustration and the relevance of the topic are mentioned in the open-ended questions. In relation to the relevance of the topic, one of the students highlighted that he has never learnt to detect manipulation strategies before. This confirms the necessity for promoting comparable skills in education. The differences between the grade levels show that especially younger students need additional support for the tasks in class.

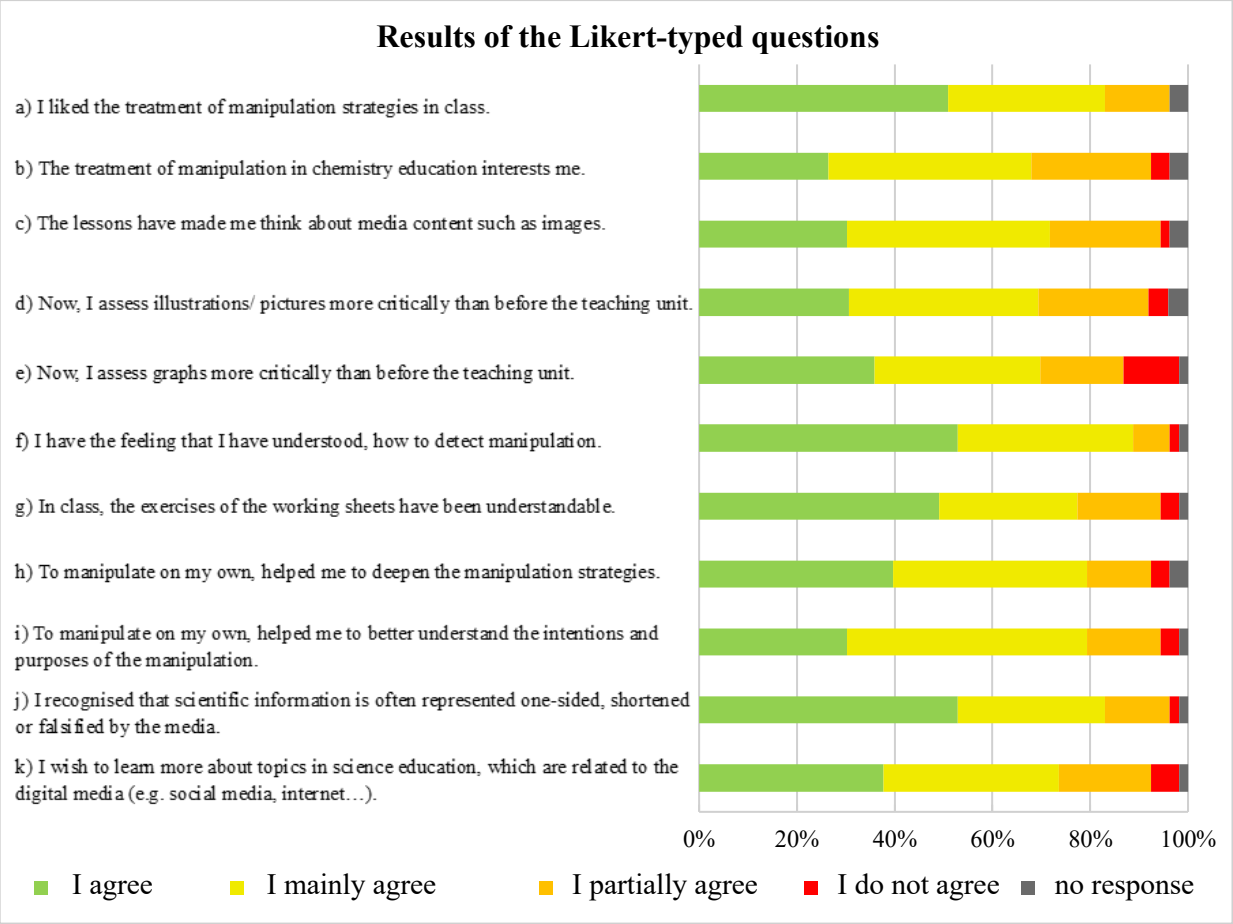
The general difficulty of the topic was also mentioned by some students, while others assessed their previous knowledge as high. The high level of previous knowledge could often not be proved by the students' performances in the exercises of the evaluation. This may be connected to the difficulties of self-assessment (Riese & Reinhold, 2014). It is also possible that some students underestimate the topic due to its close connection to everyday life, while others are more aware of the challenges associated with manipulation.

Likert-Typed Questions

Overall, the results of the Likert-type questions are positive. The results (Figure 4) show, among other aspects, that most students had the feeling to understand how to detect manipulation which is a sign of success of the unit. The majority also seem to have benefits from manipulating media content by themselves. There were major differences between the grades in terms of their perception of the comprehensibility of the tasks in class. In the eleventh grade, all students agreed or mainly agreed that the tasks were understandable. This may be because some of the younger students need additional support with the tasks. Furthermore, nobody fully disagreed that they liked the topic of manipulation strategies in class. It seems to be a motivating topic for education.

Since four students were ill during the lessons on the illustrations but took part in the evaluation, item d) was not taken into account for them (Figure 4).

Figure 4. Results of the Likert-type questions (N= 53; item d): N= 49).



Conclusions

The results demonstrate that the teaching unit seems to be able to contribute to the promotion of Scientific Media Literacy, especially concerning the media analysis (Chang Rundgren & Rundgren, 2014). The promotion is mainly designed to be preventive in order to prepare the students to deal with manipulated illustrations and graphs in the future (van der Linden, 2022). The fact that the students mainly feel secure when it comes to the detection of manipulation strategies (shown in Figure 4) is a sign that the teaching unit is able to support them.

However, the unit is not able to realize the promotion of Scientific Media Literacy on its own. Support by further units, an expansion to the other dimensions of the concept, and more practice is needed. The domain of knowledge is also integrated in the teaching unit through the scientific background of the media content and the creation of manipulated illustrations (Chang Rundgren & Rundgren, 2014), but this specific domain should also be further promoted. In addition, it would be interesting to measure students' learning process in connection with teaching units in the area of Scientific Media Literacy at different points in time following the unit. That would also reveal more about how long the effects of interventions last.

All in all, the topic of manipulation seems to be relevant for the students' daily lives, which can be supported by their answers in the evaluation. Science education plays an important role in promoting the competencies needed to address challenges related to the distortion of scientific information in the media.

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How Do Greek Students And Teachers Perceive Climate Change?

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Probing people's perceptions about climate change is crucial for the design of communicational and educational practices that will motivate environmentally responsible behaviour. In this study, we explored Greek students' and teachers' perceptions about climate change. The participants (N = 166) perceive climate change to be real and primarily human caused and as a certain and present risk for them and their country. Perceptions of scientific uncertainty vary, with secondary school educators and students expressing higher levels compared to the ones of educators and students in tertiary education. Moreover, the impacts of climate change elicit moderate levels of concern among participants. A correlation was found between participants' perceptions of psychological temporal distance from climate change and their educational group (secondary/tertiary education teacher or student). Finally, participants mainly trust scientists, environmental organizations and teachers as sources of information regarding climate change. The findings contribute to the understanding of how the stakeholders of the Greek educational community perceive climate change, which should guide the design of more targeted and effective educational strategies.

Keywords: Assessment, Public Understanding of Science, Quantitative Research

Introduction

Climate change presents a significant and urgent threat to humanity (Mbah, 2024). Public perception of climate change plays a vital role for the development of effective solutions (Weber, 2010). This is because successful climate policies necessitate public support, which relies on well-informed citizens advocating for meaningful action (Pidgeon & Fischhoff, 2011).

Many studies have examined people's climate change perceptions of various types and by using diverse measurements. The current study concerns six distinguishable types of climate change perceptions, namely (a) the existence and causes of climate change, (b) concerns about the effect of climate change, (c) the personal risk of the effects of climate change, (d) the psychological temporal distance (whether people perceive the effects of climate change as occurring soon or in the distant future), (e) the perceived scientific uncertainty, and (f) the trust of information sources.

The first two types of perceptions fit with arguments of climate change sceptics, which first focus on denial of the reality of climate change, then move towards attributing it to natural causes rather than human activity and downplaying the extent to which climate change would bring about negative consequences (van Valkengoed et al., 2021).

The psychological temporal distance and uncertainty of the effects of climate change have been suggested as dimensions of people's climate change perceptions (Spence et al., 2012). Uncertainty refers to complex, encompassing scientific disagreement and the inherent unpredictability of climate systems and it is often confused with scepticism (Spence et al., 2012; Weber, 2010). Significant scientific uncertainty surrounds the potential impacts of climate change due to the immense complexity of climate systems and their interactions with human and biological systems. Our understanding of these intricate systems remains incomplete and there may be large considerable scientific disagreement and uncertainty around the potential impacts

of climate change. On the other hand, scientific disagreement and uncertainty are the sceptics' justification for the denial of climate change. Therefore, it is crucial to be precise when discussing scepticism and uncertainty related to climate change. Media often misrepresents scientific controversies and tends to focus on minimizing consensus, thus promoting the creation of confusion among the public (Pidgeon & Fischhoff, 2011). This misinformation poses a challenge for scientists and educators. People generally prefer certainty, and communicating uncertainty can hinder climate action (Weber, 2010). However, the interplay between uncertainty and other climate change perceptions remains understudied (Spence et al., 2012).

Climate change perceptions differ significantly between scientists and the public (Mbah, 2024; Myers et al., 2021). This disparity arises partly from the abstract nature of climate change, making it difficult for individuals to accurately perceive based on personal experience (Weber, 2010). Therefore, scientists, media, and educators play crucial roles in detecting and communicating climate change information. Moreover, people's trust and attention are key factors in how they perceive climate change information and individuals are more likely to pay attention to and incorporate information from trusted sources (Weber, 2010). The way climate change information is communicated and amplified by scientists, media, cultural groups, and other sources significantly shapes individuals' perceptions and actions to this critical issue (Weber, 2010).

Most research on climate change perceptions has focused on adults, while the need for effective educational strategies necessitates a holistic exploration of both student and teacher perceptions. Moreover, in Greece there has been so far no systematic research aiming at measuring the climate change perceptions of the educational community. Taking into consideration the discussion above, the present study addresses the following research question:

What are the climate change perceptions among Greek students and teachers in secondary and tertiary education?

Method

Participants

The participants are upper secondary education students (n=28, age 16–17 years) and teachers (n=34, age >25 years), as well as undergraduate students (n=89 age 18–22 years) and tertiary education teachers (n=15, age >35 years). The survey was conducted online via Google Forms.

Instrument

The instrument consists of 3 parts. The first part is composed of 25 items related to perceptions about climate change assessed by a Likert-type scale ranging from "strongly disagree" (0) to "strongly agree" (10). Moving from "strongly disagree" to "strongly agree," positive items were scored from 0 to 10, respectively, while negative items were scored in the reverse order. In the instrument the terms climate change and global warming are used interchangeably, since they are usually treated as equivalent in public discourse.

An exploratory factor analysis (EFA) followed by confirmatory factor analysis (CFA) of our data resulted in four scales corresponding: (a) Personal Risk Perceptions (5 items, Cronbach's Alpha=0.819), (b) Global Warming Beliefs (8 items, Cronbach's Alpha=0.812), (c) Scientific Uncertainty (4 items, Cronbach's Alpha=0.703), and (d) Climate Change Concerns (3 items, Cronbach's Alpha= 0.821). The values of Cronbach's Alpha exceed 0.7 for all four scales, thus indicating satisfactory internal consistency (Field, 2013). Detailed results of EFA and CFA accompanied by the reliability and validity evidence of the data gathered are reported in a submitted manuscript.

The second part consists of ten items related to trust in ten different information sources (family members, friends, scientists, the government, energy suppliers, environmental organizations, media, social media, internet, teachers). Participants' responses to each item were assessed using a Likert-type scale ranging from "no trust" (0) to "absolute trust" (10).

Finaly, the third part is an item related to the psychological temporal distance. Participants were asked to answer question "When do you think global warming will start to harm people in Greece?" choosing among (a) they are being harmed right now, (b) in 10 years, (c) in 25 years, (d) in 50 years, (e) in 100 years, (f) beyond the next 100 years, and (g) never. All the items were developed based on previous research (Özdem et al., 2014; Spence et al., 2012).

Results

Perceptions About Climate Change

The descriptive statistics (mean value, standard deviations) regarding the four scales derived from the exploratory factor analysis are shown in Table 1. Data is reported for the whole sample as well as for each of the four distinct demographic groups which comprise it.

Table 1 Descriptive statistics of four scales corresponding to perceptions about climate change

		Total (N=166)	Secondary students (N=28)	Secondary teachers (N=34)	Undergraduate students (N=89)	Tertiary teachers (N=15)
Scale		Statistics				
Personal risk perceptions	Mean	8.12	7.47	8.42	8.16	8.33
	SD	1.44	1.76	1.36	1.29	1.62
Global Warming Beliefs	Mean	8.51	8.17	8.36	8.64	8.75
	SD	1.20	1.21	1.45	1.10	1.10
Scientific Uncertainty	Mean	5.91	5.71	5.68	6.01	6.18
	SD	1.95	1.54	2.25	2.02	1.56
Climate Change Concerns	Mean	6.65	6.87	6.82	6.43	7.13
	SD	2.29	2.28	2.54	2.18	2.39

[a]*All scale values range between 0 and 10*

[b]*Higher scores correspond to lower uncertainty*

The personal risk perceptions scale reveals the subjective nature of how people perceive the risks associated with climate change. For instance, the item "Global warming will harm me personally" directly reflects an individual's perception of personal risk while the item "Global warming will harm people in Greece" reflects the participant's risk perception related to locality.

In this study, Greek students' and teachers' personal risk perceptions of climate change have mean values ranging from 7.47 to 8.42 indicating their high awareness about the effects of climate change in their country and lives.

The global warming beliefs scale is comprised of 8 items that reflect different beliefs about: (a) the causes of global warming, (b) the personal thoughts and scientific consensus about whether global warming is happening, (c) the severity of the issue, and (d) the potential consequences of global warming. As shown in Table 1, all participants responses' mean values fall in the range between 8.17 and 8.75, thus indicating that they think global warming is happening and that it is mostly anthropogenic. They do not consider the seriousness of climate change as exaggerated as they perceive that it will harm the living organisms and the future generations.

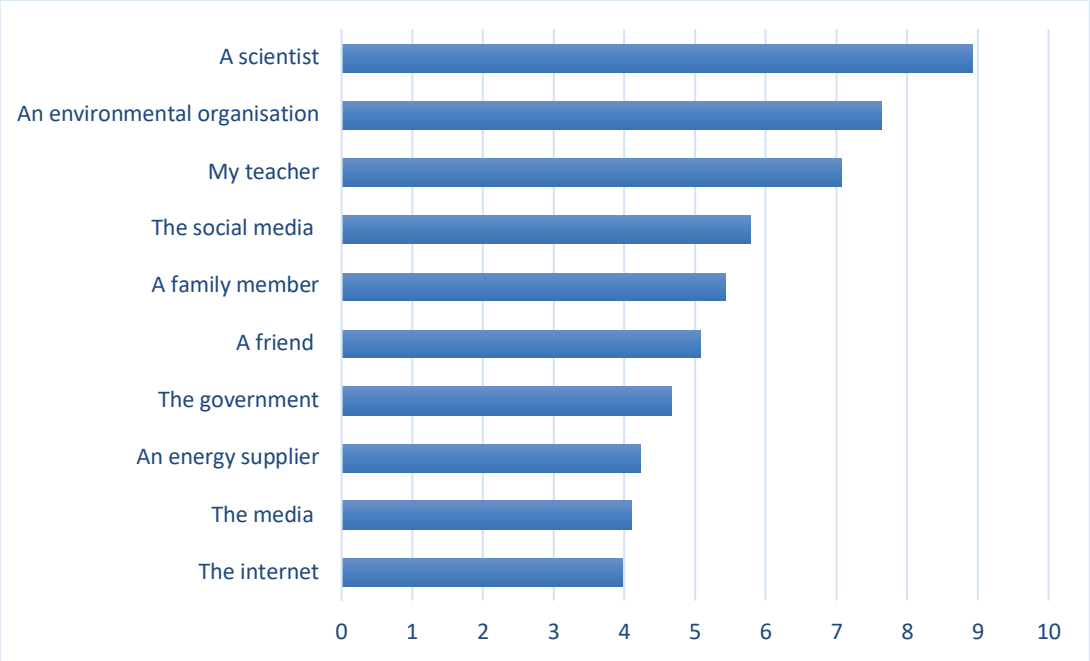
The scientific uncertainty scale consists of 4 items, which focus on the perceived or actual lack of scientific consensus, the uncertainties and the debate regarding climate change. The participants' responses reveal varying levels of perceived scientific uncertainty. Secondary teachers and students exhibited higher levels, while tertiary teachers and undergraduate students demonstrated lower levels. An analysis of participants responses to each item reveals that all of them concurred that "most scientists agree about climate change impacts" and that "there is not too much conflicting evidence about climate change." Conversely, tertiary teachers acknowledged that "there is a disagreement among scientists about whether global warming is happening" but "it is certain what the effects of climate change will be" while the other groups of participants held opposing views.

The 3 items that constitute the climate change concerns scale reflect the emotional anxiety experienced by individuals due to concerns about the consequences of climate change. The results indicate that climate change impacts elicit moderate levels of worry among Greek secondary and tertiary students and teachers, with mean scores ranging between 6.43 and 7.13.

Trust In Information Sources

Scientists (Mean=8.92, SD=1.16), followed by environmental organizations (Mean=7.63, SD=2.00) and teachers (Mean=7.63, SD=2.00) stand higher regarding the participants' trust as sources of climate change information. On the other hand, participants trust much less the internet (Mean=3.97, SD=2.40), media (Mean=4.10, SD=2.53), energy suppliers (Mean=4.22, SD=2.73), and the government (Mean=4.67, SD=2.70), as Figure 1 represents.

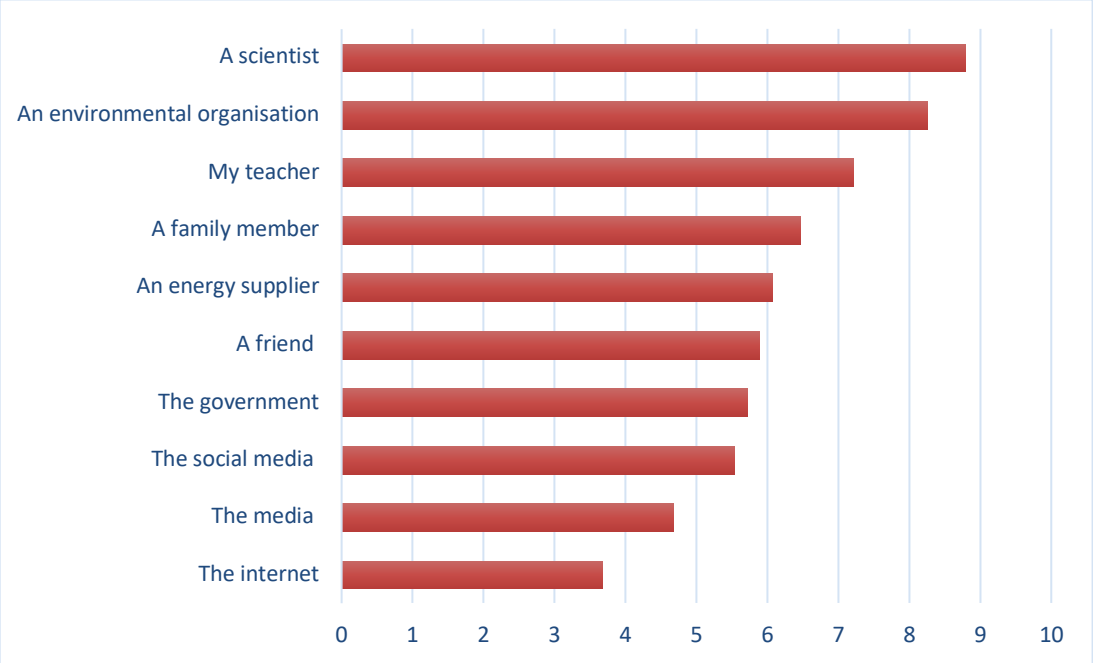
Figure 1. Mean responses on trusted sources regarding climate change



An interesting finding is that upper secondary students also trust more the scientists (Mean 8.79, SD 1.03), the environmental organizations (Mean 8.25, SD 1.38) and their teachers (Mean 7.21, SD 1.95) rather than the social media (Mean 5.54, SD 1.84) as shown in figure 2. Although, research has been shown that secondary students usually show a high level of trust in social media platforms (Haile, 2024), the upper secondary students of this study are not trusting information found on social media as much. Lower secondary Turkish students also identified scientists as a trustable source of information (Özdem et al., 2014). Zilz and Höttecke (2025) proposed that trust strategies, sources or representatives are evaluated based on the three indicators of trustworthiness: expertise, integrity, and benevolence. These indicators are indeed largely served by scientists, teachers, and environmental organizations. The academic profile, the specialized

knowledge and the transparency and effort to convey current scientific knowledge as accurately as possible without any conflicting interests, are the characteristics of these sources which contribute to trustworthiness.

Figure 2. Upper secondary students' mean responses on trusted sources regarding climate change.



Psychological Temporal Distance

With respect to the perceived psychological temporal distance, about three quarters of undergraduate students (73.0%), as well as secondary (79.4%), and tertiary teachers (73.3%), but much less upper secondary students (35.7%) think people in Greece are being harmed by global warming right now. Specifically, only 10 out of 28 upper secondary students reported that they are being harmed by global warming right now, while 5 of them reported that they will be harmed in the distant future either in 100 year (one student) or beyond the 100 years (three students), and one responded "never".

The results of a chi-square test (bootstrap with number of samples 1000 and confidence interval level 95.0%) suggest that there is a correlation between perceptions of psychological temporal distance for climate change and the four educational groups (χ^2=25929.785, df=18, p<.001).

Conclusions

Knowledge of the perceptions regarding climate change can help the design of effective strategies to promote environmentally responsible behaviour among the public. Participant responses strongly suggest a consensus that global warming is real and primarily human caused. They do not view climate change as overstated due to concerns about its impact on living organisms and future generations. Their scientific uncertainty perceptions vary with secondary teachers and students expressing higher levels of uncertainty relative to tertiary teachers and undergraduate students. Most secondary and tertiary educators, along with most undergraduate students, perceive that people in Greece are currently experiencing harm from global warming. However, this perception is significantly lower among upper secondary students. A correlation between participants' perceptions of psychological temporal distance for climate change and the four educational groups was found. The spatial and temporal disconnection of causes and effects which characterize complex systems, such as the climate, often causes major challenges in understanding the climate change effect among younger students (Roychoudhury et al., 2017).

Moreover, the time delay (temporal disconnection) may lead to personal frustration, as individuals' climate-friendly actions do not produce immediately visible impacts, which can reduce motivation to engage in such behaviours (Gifford, 2013).

Finally, participants mainly trust scientists, environmental organizations and teachers as sources of climate change information. This is a hopeful finding as previous research indicates that trust in scientists and environmental organizations is positively linked to climate-friendly actions (Cologna & Siegrist, 2020).

The results of this study indicate that it is very important to focus on secondary education. The findings highlight the need for designing risk communication techniques to reduce psychological distance and to engage secondary school students with climate change. It is very important to use trusted sources in this effort. Thus, appropriate activities could be designed at school with a cooperation of teachers, scientists and environmental organizations.

Moreover, since such studies can be used to design a roadmap aimed at raising public awareness about climate change, it seems very important to conduct them in other countries, and therefore different cultural contexts, as well.

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How Physics Teachers Think About Science – Physics Teachers' Views Of Science Compared To Researchers' Views

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Even though Nature of Science (NOS) and Scientific Inquiry (SI) are important aspects of the educational objectives for science lessons, as defined in the curriculum in Germany and other countries, research has shown that teachers often have insufficient professional knowledge in this area. Against this background, we have set up an outreach program in the Collaborative Research Centre 'SFB1245: Atomic Nuclei: Fundamental Interactions to Structure and Stars' at TU Darmstadt to identify and develop best practices for teaching NOS and SI at school. For this, teaching materials and handouts for teachers are being developed. In order to take into account the wishes and needs from a school perspective as well as the scientists' views, both teachers and researchers are involved in the development of these materials. The accompanying study aims to determine the extent to which this collaboration positively influences the participating teachers' ideas about NOS and SI. As a first step, we have conducted a survey about the views of secondary school physics teachers about NOS and SI and contrasted it against the researchers' views in order to shed light on the baseline condition of our sample. In this contribution we will present and interpret the results of this survey. Building on this, we argue that the most relevant aspects of NOS and SI to address within the materials include the principle of research being guided by questions, as well as the constructive role of errors and interactions between researchers.

Keywords: Nature of Science, Scientific Literacy, Teacher Education

Introduction

Knowledge about Nature of Science (NOS) and Scientific Inquiry (SI) has been an educational goal since the beginning of the 20th century (Central Association of Science and Mathematics Teachers, 1907). Even today, this knowledge has not lost its importance and is regarded as being fundamental to scientific education in the sense of scientific literacy (OECD, 2017). Nevertheless, research has shown that students' ideas about science are heterogeneous and often inadequate (Höttecke, 2012).

While knowledge about NOS and SI as educational goals should be fostered in the classroom, teachers themselves need to have the necessary knowledge about it in the first place (Kremer, 2010). However, research has revealed that teachers often have insufficient professional knowledge in this area (Billion-Kramer et al., 2020) and even if they have adequate ideas about it, this does not necessarily entail integration into their teaching (Bartos & Lederman, 2014). Reasons for this might be the complexity of the area and a lack of familiarity with the numerous aspects, as well as its inadequate consideration in teacher training, among other factors (Hößle et al., 2004).

Against this background, we conclude that there is a need for teacher training as well as teaching materials and handouts for teachers to incorporate NOS- and SI-aspects into their classrooms. We have therefore set up a project to address this, as part of the outreach program in the CRC 1245 (Collaborative Research Centre 'SFB1245: Atomic Nuclei: Fundamental Interactions to Structure and Stars') at TU Darmstadt. This is a collaboration of various research groups, who work together on overarching issues and are funded by the German Research Foundation (DFG). In this project, a group of teachers and researchers (development group) will collaborate to develop these teaching materials and handouts. The accompanying study aims to determine the extent to which this collaboration positively influences the participating teachers' ideas about NOS and SI.

In this contribution we will present and interpret the results of a preliminary study about the views of secondary school physics teachers on NOS and SI. We have conducted this study in the vicinity of our university, the sample including all teachers of the development group among others, to gain insight into the baseline conditions for our project. The aim of this study is to contrast the teachers' views against the researchers' views, and to derive the most relevant aspects of NOS and SI to address within the teaching materials and handouts.

Methods

For this purpose, we used the VOS questionnaire and the corresponding coding manual developed by Bächtold et al. (2021). It contains eleven items that cover eleven aspects (VOS 1 – 11) of NOS and SI, as shown in Table 1.

Table 1. Selected epistemological points - VOS questionnaire (Bächtold et al., 2021)

Aspect	Definition of the aspect	NOS/SI
VOS 1	Scientific knowledge is based on empirical support.	NOS
VOS 2	There is no single scientific method.	SI
VOS 3	Scientific investigations are motivated and guided by questions.	SI
VOS 4	Scientific knowledge is always tentative.	NOS
VOS 5	Science interacts with the socio-economic and cultural context.	SI
VOS 6	The empirical data on which scientific knowledge is based are always theory-laden.	NOS
VOS 7	The models built by the scientists are distinct from the empirical reality.	NOS
VOS 8	Errors may play a constructive role in the development of science.	SI
VOS 9	Interactions between scientists actively contribute to the construction and validation of scientific knowledge.	SI
VOS 10	Realism versus instrumentalism with respect to the role of models.	NOS
VOS 11	Relativism or rejection of relativism concerning the influence of the socio-economic and cultural context on the construction of scientific knowledge.	SI

These VOS-aspects are based on the NOS-aspects proposed by Lederman (Lederman et al., 2002) and the SI-aspects described by Lederman et al. (Lederman et al., 2014). Building on these frameworks, Bächtold et al. (2021) combined these NOS- and SI-aspects into an integrated set of dimensions capturing teachers' views of science and additionally introduced several new aspects, such as aspect VOS 8, which addresses the constructive role of errors, and aspect VOS 9, which focuses on interactions among scientists.

Following the coding manual by Bächtold et al. (2021), the qualitative coding of the questionnaire for each VOS-aspect is based on one to three items, whereby most items are each incorporated into the evaluation of several aspects. For VOS 1, 2, 4, 5, 7, 8 and 9 responses are assigned to one of the following categories: novice, rather novice, rather expert, expert, depending on the context or not interpretable. The aspects VOS 3 and VOS 6 are coded dichotomously as either novice or expert. For VOS 10, coding distinguishes between naïve-, balanced realism or instrumentalism, while VOS 11 is coded as strong-, rather strong-, rather moderate-, moderate relativism, rejection

of relativism or not interpretable. We translated the VOS questionnaire into German and conducted several 'think-aloud' sessions with students and researchers at our university (n=7). In addition, the questionnaire was administered to a group of university students (n=12) to pretest the translated instrument and to refine the corresponding coding manual. Additionally, the data were double-coded, followed by a coding reconciliation process.

After that, a digital version of the questionnaire was distributed via email to numerous secondary schools and teacher education institutions in the vicinity of our university between August and November 2024. In total, 58 teachers responded, of whom 42 completed the questionnaire and could therefore be included in the analysis. This group of teachers comprised 35 in-service physics teachers and seven pre-service physics teachers. Among these participants, 25 were male and 17 were female. For the analysis, only the questionnaires completed by in-service and pre-service physics teachers were considered, resulting a final sample of 42 physics teachers (17 female, 25 male). Seven in-service teachers and one pre-service teacher have a PhD.

In addition, the digital questionnaire was administered to researchers during a CRC 1245 workshop in November 2024. Due to time constraints, researchers were asked to respond only to items addressing selected aspects (VOS 1, VOS 3, VOS 4, VOS 7, VOS 8 and VOS 9) which were of particular interest for contrasting teachers' and researchers' views. In this group, 45 researchers participated, of whom 32 completed the questionnaire and were included in the analysis. The sample comprised 13 experimental physicists and 19 theoretical physicists, all specializing in nuclear and astrophysics as part of the CRC. The group included six project leaders (mostly professors), 18 PhD students, and eight researchers in other positions.

Results

Presentation Of Teachers' Results

The results of the analysis for the teachers are presented in Tables 2, 3 and 4 as rounded percentages, with absolute numbers given in brackets.

The evaluation shows that, particularly for the first aspect (VOS 1), the ideas of 43 % of the teachers are context-dependent, while 21 % are categorized as novices. This indicates that teachers hold naïve views on VOS 1, at least in certain contexts. The ratings for VOS 3 are also worrying, as 43 % of the teachers are categorized as novices, meaning that almost half of the teachers have inadequate conceptions of this aspect. Similarly, for VOS 6, nearly half of the teachers (48 %) demonstrate inadequate ideas. Aspect VOS 8 reveals that many teachers are categorized as rather novice (48 %), whereas only 41 % are classified as experts. For VOS 9, a substantial proportion of teachers (30 %) are also categorized as rather novice, indicating that many teachers lack adequate understanding of this aspect as well.

Table 2: Results VOS 10 aspect teachers in % (n=42) and the number in columns.

Naïve realism	14 (6)
Balanced realism	7 (3)
Instrumentalism	71 (30)
Others	7 (3)

Table 3. Results VOS Questionnaire teachers in % (n=42) and the number in columns.

	VOS 1	VOS 2	VOS 3	VOS 4	VOS 5	VOS 6	VOS 7	VOS 8	VOS 9
Not interpretable	12 (5)	0 (0)	2 (1)	0 (0)	0 (0)		0 (0)	12 (5)	0 (0)
Novice	21 (9)	0 (0)	43 (18)	0 (0)	7 (3)	48 (20)	14 (6)	0 (0)	0 (0)
Rather Novice	5 (2)	10 (4)		14 (6)	0 (0)		0 (0)	48 (20)	30 (16)
Depending on context	43 (18)	0 (0)		7 (3)	0 (0)		7 (3)	0 (0)	2 (1)
Rather Expert	0 (0)	29 (12)	55 (23)	52 (22)	0 (0)	52 (22)	57 (24)	0 (0)	31 (13)
Expert	15 (8)	62 (26)		26 (11)	93 (39)		21 (9)	41 (17)	29 (12)

Table 4: Results VOS 11 aspect teachers in % (n=42) and the number in columns.

Strong relativism	74 (31)
Rather moderate relativism	5 (2)
Moderate relativism	14 (6)
Rejection relativism	7 (3)
Not interpretable	0 (0)

The evaluation of the remaining aspects shows that the majority of teachers are categorized as instrumentalists for VOS 10 (71 %) and as strong relativists for VOS 11 (74 %).

A direct comparison between pre-service and in-service teachers reveals marked differences in aspects VOS 2, 3, 6, 8 and 9.

For aspect VOS 2, 43 % of the pre-service teachers are categorized as rather expert and an additional 43 % as expert, while 67 % of the in-service teachers are categorized as expert and only 24 % as rather expert. Regarding VOS 3, most pre-service teachers (71 %) are classified as

Figure 1: Results VOS 2.

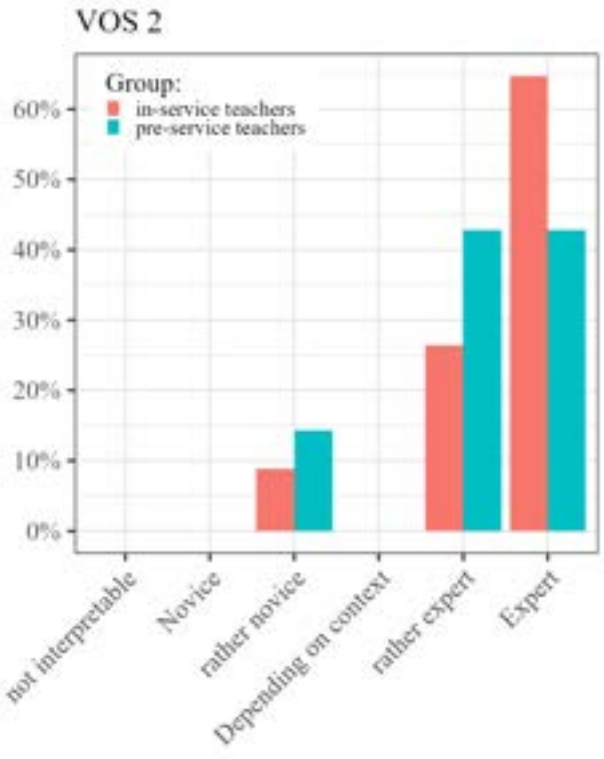


Figure 2: Results VOS 3.

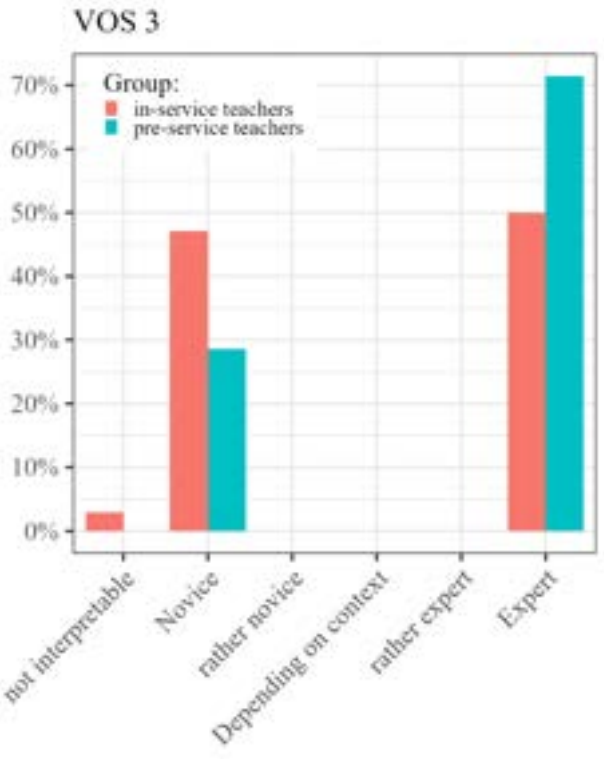


Figure 3: Results VOS 6.

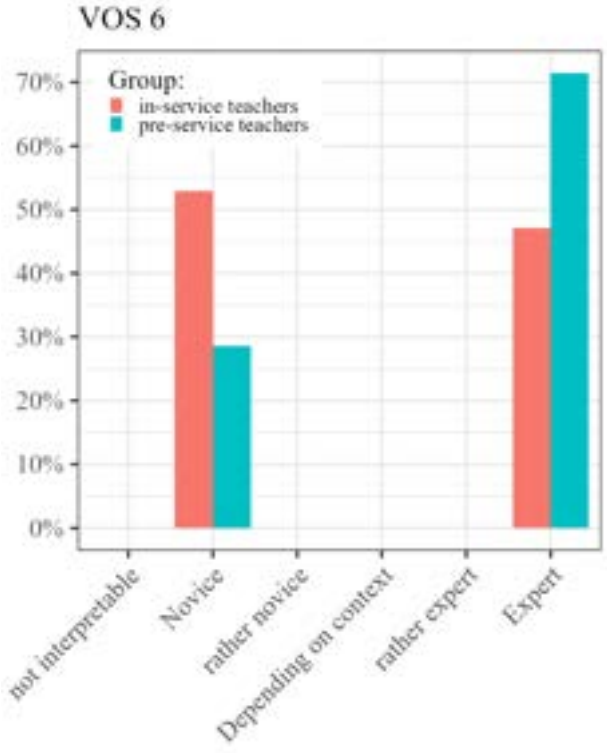


Figure 4: Results VOS 8.

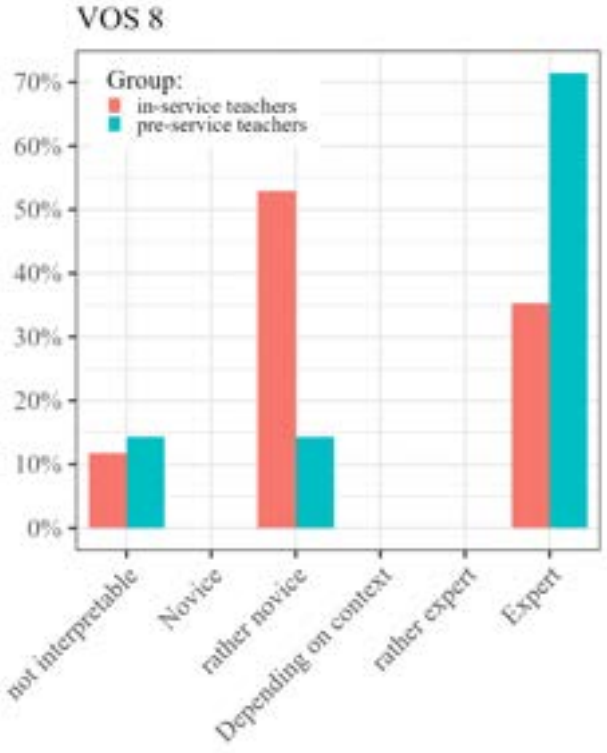
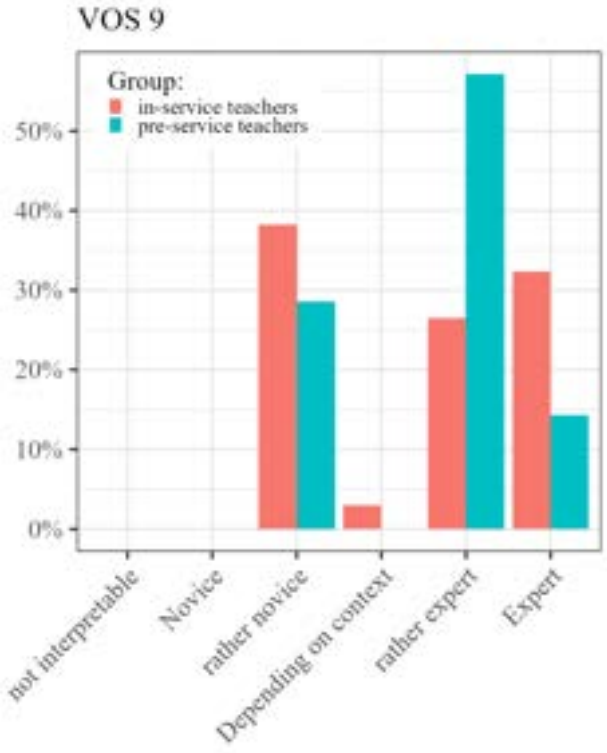


Figure 5: Results VOS 9.



experts, compared to only about half of the in-service teachers (52 %). For aspect VOS 6, again 71 % of the pre-service teachers are categorized as experts, while more than half of the in-service teachers (55 %) are categorized as novices.

A similar pattern emerges for VOS 8: 71 % of the pre-service teachers are categorized as experts and only 14 % as rather novice, while 52 % of the in-service teachers are categorized as rather novice and only 36 % as experts.

A different distribution can be observed for VOS 9. Among pre-service teachers, 29 % are categorized as rather novice, 57 % as rather expert, and only 14 % as expert. In contrast, among in-service teachers, 36 % are categorized as rather novice, 27 % as rather expert, and 33 % as expert.

Interpretation Of Teachers' Results

The analysis of the results indicates that many teachers show limited familiarity with several aspects of the VOS framework. Across multiple dimensions, a considerable proportion of teachers were categorized at lower levels, suggesting that key characteristics of scientific practice are not consistently represented in their responses. Overall, the findings point to a fragmented and context-dependent understanding rather than a comprehensive and integrated view of scientific investigations.

In general, the results suggest that many teachers have had little direct engagement with scientific research practices themselves. Their reported understanding appears to be shaped primarily by school-based experiences and formal instructional settings rather than by active involvement in research processes. Furthermore, the contact with scientific concepts during teacher education seems to have been only partially aligned with the broader epistemic aspects addressed in the framework, with a stronger focus on content knowledge and procedural routines than on overarching features of scientific inquiry.

Differences between in-service and pre-service physics teachers were observed, indicating variation in how these aspects are understood at different stages of professional development. While pre-service teachers tended to demonstrate more advanced understandings in several areas, in-service teachers also showed greater familiarity with some selected aspects, potentially reflecting professional experience. However, these differences remain descriptive, as the present data do not allow firm conclusions about their underlying causes.

Overall, the results suggest that substantial portions of both groups lack a fully developed understanding of central characteristics of scientific practice. This points to a need for further consideration of how such aspects are addressed in teacher education and professional development, particularly with respect to connecting theoretical exposure during studies more closely to the core epistemic features of scientific research.

Comparison Of Teachers' Views To Researchers' Views

To enable a more differentiated interpretation of the results, the teachers' views were compared with researchers' views of science.

The results of the analysis for the researchers are shown in Table 5.

Table 5. Results shortened VOS Questionnaire CRC-researchers in % (n=38) and the number in columns.

	VOS 1	VOS 3	VOS 4	VOS 7	VOS 8	VOS 9
Novice	38 (12)	17 (5)	0 (0)	12 (3)	0 (0)	0 (0)
Rather Novice	9 (3)		4 (1)	0 (0)	3 (1)	0(0)
Rather Expert	6 (2)		43 (12)	58 (15)	0 (0)	26 (7)
Expert	13 (4)	83 (24)	32 (9)	27 (7)	90 (26)	70 (19)
Depending on context	22 (7)		21 (6)	4(3)	0 (0)	4 (1)
Not Interpretable	13 (4)		0 (0)	0 (0)	7 (2)	0 (0)

The findings show that for aspect VOS 1, even researchers received relatively few expert ratings, while a considerable proportion (38 %) were categorized as novices. One possible explanation is, that the researchers' responses to one of the relevant items were highly specific to a particular case and therefore did not fully align with the coding scheme applied in the analysis. An analysis of the shortened VOS questionnaire completed by CRC-researchers working in experimental or theoretical physics reveals marked differences for aspect VOS 1. Theoretical physicists show a balanced distribution between notice and expert (21 % each) as well as between rather novice and rather novice (5 % each). In contrast, experimental physicists exhibit a clear tendency toward novice categorizations, with 62 % categorized as novice and no expert categorizations observed.

For aspects VOS 3 and VOS 4, researchers show a higher proportion of expert ratings compared to teachers. The result for VOS 7 is almost identical for researchers and teachers. A substantial

difference is evident for VOS 8, where the majority of researchers are categorized as experts, while about half of the teachers are categorized as rather novices. Similarly, nearly all researchers are categorized as experts or rather experts for VOS 9, while 40 % of the teachers are classified as rather novices.

Discussion

Regarding limitations, we acknowledge that the sample size of this study is relatively small. Nevertheless, the preliminary findings allow for several important conclusions relevant to the present project. The results indicate that the views of many teachers on aspects of the nature of science (NOS) and scientific inquiry (SI) are inadequate, especially for aspects VOS 1, 3, 6, 8 and 9, teachers' results showed ideas that do not reflect reality. For VOS 3, 6 and 8 pre-service teachers demonstrate more informed views than in-service teachers.

These aspects address key characteristics of scientific practice, namely that scientific knowledge is based on empirical support (VOS 1), that scientific investigations are motivated and guided by questions (VOS 3), that scientific knowledge is based on theory-laden empirical data (VOS 6), the constructive role of errors in scientific progress (VOS 8) and the importance of interactions among scientists in the development of science (VOS 9).

The results therefore suggest that pre-service teachers possess a more advanced understanding in these areas, highlighting the need for targeted interventions particularly for in-service teachers. The relevance of this is further underlined by the fact that in-service teachers have few opportunities to gain deeper insight into current research and scientific processes that they can incorporate into their teaching.

Furthermore, the views of researchers, especially those working in experimental physics, are not consistently categorized as experts in the present analysis, despite their professional expertise in NOS- and SI-aspects due to their work. The results for this question suggest some limitations in the coding manual, and interpretations based on it should be approached with caution. Revising the manual could help provide a clearer assessment of the underlying aspect.

Based on these findings, we argue that there is a clear need for further teacher training as professional development opportunities, as well as for the development of teaching materials and handouts to support teachers in addressing these topics in the classroom. Such materials should place particular emphasis on aspects VOS 3, 6, 8, and 9 by highlighting the interplay between theoretical and experimental physics, providing insights into the productive role of errors in scientific processes, and emphasizing the collaborative nature of scientific research. Within this context, the CRC provides an excellent framework for the implementation of such initiatives.

Acknowledgement

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Fighting Fake News In Science Project: An Action Research Study Involving Brazilian Students, Teachers And Academics

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Contemporary society faces challenges in combating Fake News (FN), especially in science-related topics. During the COVID-19 pandemic, FN intensified globally, especially in Brazil, where the political misinformation, spread widely via social media, impacts collective health. The lack of media criticism and scientific literacy exacerbated the issue, highlighting the need for educational initiatives. In response, a Participatory Action Research (PAR) project titled "Fighting Fake News in Science" was launched, involving academics, teachers, and students from a public university and a school in Rio de Janeiro. Over one school year (2022), the team followed PAR's cyclical stages—Plan, Act, Reflect, Evaluate—to address misinformation about COVID-19. The methodology involved: establishing relationships and a common agenda with the team; collaboratively deciding on issues, research design, ethics, and accountability; Planning, scheduling and implementing an action plan, working together to collect and analyse data, and disseminating our findings. The action plan involved four phases where students chose, studied and analysed four FN (e.g., alkaline foods cure COVID-19) using an information disorders framework. Guided by teachers, they conduct inquiry-based activities to deconstruct FN through scientific experiments, fostering critical thinking and collaborative problem-solving. The findings were disseminated via Instagram® (@meninas_fakenews), a lecture, a workshop, and a local conference. The project achieved significant impact, engaging over 200 participants and inspiring students, particularly girls, to consider careers in Science. Testimonials highlighted the transformative experience, with students expressing gratitude for the opportunity to lead, learn, and grow. The project underscores the importance of empowering communities to combat misinformation and promote scientific understanding.

Keywords: Science Education. Misinformation. Participatory Action Research.

Introduction

Contemporary society is marked by the constant and diverse flow of information facilitated by the internet, which has democratised knowledge but also brought challenges regarding the credibility of information (Flanagin & Metzger, 2000). Fake News (FN) and manipulative reporting have gained notoriety in recent years and are often labelled as one of the biggest threats to democracy (Hinds, 2019). According to Tandoc et al. (2017), FN can be defined as false and sensationalist information disseminated as news. For Wardle and Derakhshan (2017), FN, conspiracy theories, clickbait, rumours, and hoaxes are part of a more complex framework, information disorders.

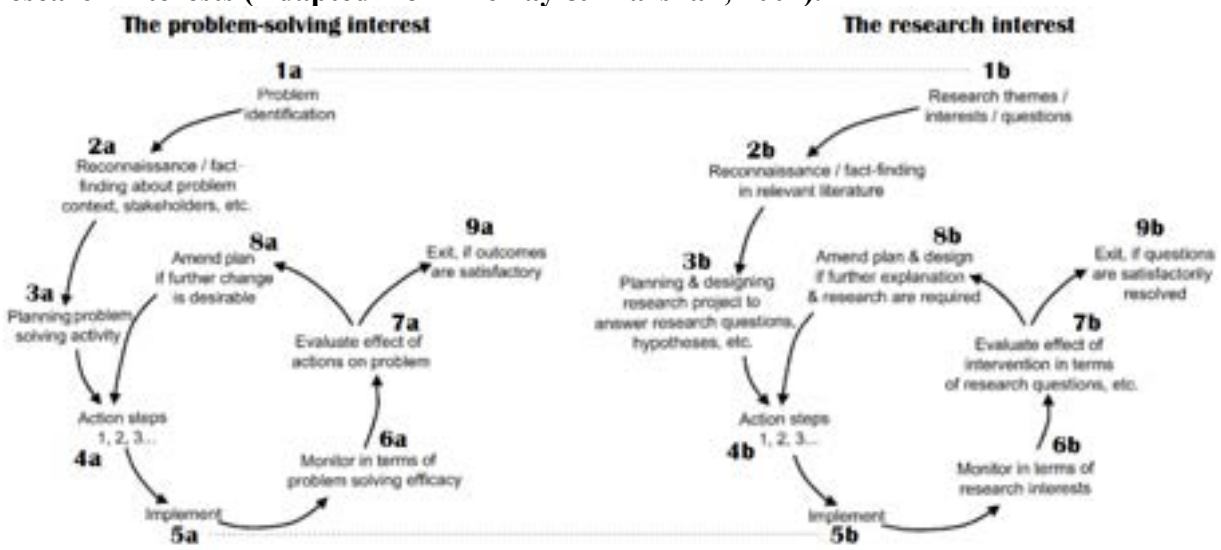
In Brazil, during the COVID-19 pandemic, the dissemination of FN intensified, representing a danger to public health, as many people accepted and shared information without critical thinking (Islam et al., 2020). The FN spread at the beginning was characterised by political content regarding misinformation about the number of cases and deaths and prevention measures and treatment, mainly disseminated through WhatsApp® and Facebook® social media (Barcelos et al., 2021).

The lack of scientific knowledge contributes to people spreading misinformation, especially regarding Natural Science disciplines, Chemistry, Physics and Biology. Scientific literacy, a polysemic term commonly used to describe an understanding of science and its societal applications (Laugksch, 2000), is crucial to empowering citizens to reckon with and combat these

untruths, promoting an adequate understanding of science and its practices. This highlighted the importance of educational initiatives. In this context, academics, high school teachers and students engaged in a project entitled Fighting Fake News in Science aimed to empower the local community to become protagonists in fighting science-based FN. This paper aims to present the Project, conducted through a Participatory Action Research (PAR) study.

Action research is an approach that integrates action and research, aiming to address practical problems while generating new knowledge (McNiff, 2013). More specifically, PAR is focused on addressing a specific local issue and attempts to empower participants or bring about social change. PAR is a cyclical process with four general phases: Plan, Act, Reflect and Evaluate. The outcomes from one cycle are used as the basis for continued exploration of practice in the following cycle. The PAR *Fighting Fake News in Science* Project was conceptualised and conducted through the dual cycle process (Figure 1) adapted from McKay and Marshall (2001), focused on both problem-solving (Steps 1a-9a) and research interests (Steps 1b-9b).

Figure 1: The dual cycle process in action research, focused on problem-solving and research interests (Adapted from McKay & Marshall, 2001).



The four stages of the PAR Project were:

- 1st Stage (PLAN) – Steps 1, 2 and 3: Examining the situation, identifying the problem, and planning the activities.
- 2nd Stage (ACT) – Steps 4 and 5: Obtaining the necessary information to answer the question, defining which sorts of data are needed and how to collect them, and developing and implementing an action plan.
- 3rd Stage (REFLECT) – Step 6: Monitoring, analysing, interpreting, and sharing the data.
- 4th Stage (EVALUATE) – Steps 7, 8 or 9: Determining improvements based on a new standard, and creating new plans to implement changes.

Results And Discussion

To select a community setting and co-researchers who agree to explore a feasible Project, we establish relationships and a common agenda to collaboratively decide on issues. The team included: two academics/full professors (Chemistry and Science Education) from the Fluminense Federal University (UFF), four high school teachers (Biology, Chemistry, Portuguese and Sociology) from a public school in Rio de Janeiro, the school's Principal, who was a Master's

student in Science Education at UFF, one undergraduate student at UFF (pre-service Chemistry teacher) and three senior high school students.

The Project was conducted through five-hour monthly meetings during one Brazilian school year (January-December 2022). The first task (*January*) was to decide on the issue the research would focus on. The students conducted an online survey with the local school community (students, parents, staff, teachers), asking them to differentiate between true and fabricated news and justify their answers. Almost 85% of the community could not distinguish between fact and false information; the COVID-19 news was the most difficult for them. Major justification relies on a lack of media criticism (e.g., not checking the information source) or science literacy (e.g., not understanding the vocabulary). Similar results were found in the recent Organization for Economic Cooperation and Development report (OECD, 2024), in which Brazil and Colombia rank lowest in identifying false content online.

Then, the team decided (*February*) to focus the problem on COVID-19 FN, involving Chemistry and Biology contents, defining the question they would like to answer: *How to improve media criticism and science literacy about COVID-19 at our school?* The academics gathered some previous research on the topic (e.g., Puig et al., 2021) and shared it with the team in a meeting (*March*). Mediated by the Sociology teacher, the students discussed the potential benefits and pitfalls of the Project and how to deal with political sensitivities around the issue (e.g., some parents disliked the theme and did not allow their children to participate in the Project).

The next meeting (*April*) was aimed at scheduling the action plan, which was organised into four phases:

- Phase 1: Choosing a COVID-19 FN to work with – one for each student.
- Phase 2: Understanding the FN according to the disorder information framework.
- Phase 3: Conducting an inquiry-based activity to deconstruct the FN, improving scientific grasp.
- Phase 4: Reporting the results to the team and creating ways to disseminate our findings to the local community.

The team gathered (*May*) to answer some critical questions (Kindon et al., 2007): *What data collection methods do we plan to use? What ethical issues may be raised by our methods? What technical skills do team members need training in? What written or visual materials must we prepare to support data gathering? How will the team incorporate reflection and iteration into our process? How do we record and store our data?* We decided to audio record the dialogues between the team, complemented by research annotations and collect all types of products the students might develop. The academic trained the science teachers to create and apply inquiry-based activities in a classroom setting. All the students and their parents signed the Informed Consent Form.

The next five meetings were used to implement the four-phase action plan. Using social media and websites, the high school students, mentored by the undergraduate student, chose the FN they wanted to study (**Phase 1**, *June*): (1) Alkaline foods, such as lemon, pineapple, garlic and dandelion, are effective in fighting coronavirus as they alter the blood pH. (2) 99% alcohol is more effective against coronavirus than 70% alcohol. (3) Alcohol gel is ineffective against coronavirus as it contains gelatine, which keeps your hand wet for longer, so we recommend

using vinegar instead. (4) Tonic water fights coronavirus because it contains quinine, which is similar to chloroquine.

Following, the students gathered with the Portuguese teacher to better understand the FN messages and their impact on our lives (**Phase 2**, *July*). Using Wardle and Derakhshan's (2017) framework, they classified the type of disorder, identified their elements (agent, message and interpreter), used source-checking and fact-checking mechanisms and proposed what technology companies, government, civil society, and education ministry could do to fight FN in our country. They made panels and essays (Figure 2) to present their results.

Figure 2: Panels and essays used by the students to present their choices and studies during Action Phase 2.



The Chemistry and Biology teachers developed inquiry-based activities (Figure 3) to engage the students in problem-solving for each FN (**Phase 3**, *August-September*). The elements of the inquiry-based activity were (Cheung, 2007): presenting a problem situation, identifying prior knowledge, proposing a question to be answered, establishing a hypothesis, conducting laboratory tests, analysing data, explaining the results based on theory and making some conclusions. They finished this phase by presenting scientific reports.

Figure 3: Inquiry-based activity created to deconstruct the first Fake News: "Alkaline foods are effective against coronavirus".

Problem Situation

The pH of the new coronavirus varies between 5.5 and 8.5. Eating foods with a pH higher than this value is enough to fight the virus. A healthy human body has a blood pH that is neither too acidic nor too alkaline – the mark varies between 7.35 and 7.45. It is necessary to eat more alkaline foods, which are above the pH level of the virus, so that it alters the blood pH and can be fought in the body. Foods such as lemon, orange, tangerine, mango, garlic and pineapple are effective against the coronavirus.

Prior Knowledge

Ask students about what they know about the concepts of acidity, basicity and the pH scale. How do you know that a food is acidic? Can a sweet or bitter food also be acidic? What measurement indicates the acidity of a substance? What does it mean for something to be alkaline? What do you understand by pH? Would you know what the pH of the blood is? Is there any substance in the blood that alters its pH?

Problem

How can you determine if a food is alkaline? Will this food be able to change the pH of your blood?

Hypotheses

Record your answers to the questions in the "Problem" in your notebook.

Laboratory

Materials: Pipette with distilled water; Glass beakers; Erlenmeyer flask; 25 test tubes on a stand; Test tube Pasteur pipettes; Graal and pistil; Glass funnel; Filter paper; Universal support and ring; Phenolphthalein solution; Ready-made solutions of pH 2, 5, 7, 10 and 13; pH indicator strip 0 to 14; Hot water; Various foods: red cabbage, lemon, avocado, garlic, mango, tangerine, pineapple, orange, egg, lemon soda, coffee, milk. Procedures

Procedure:

A) Predicting the acidity of foods

- ✓ Divide into groups with three or four students.
- ✓ Individually, predict the acidity of the foods listed: Lemon, Avocado, Garlic, Mango, Tangerine, Pineapple, Orange, Vinegar, Sparkling water, and Coffee.
- ✓ Organise your answer in a Table - write A if you think the food contains acidic substances, write B if you think it has a basic (or alkaline) character, and write N if you think the food has a neutral pH, that is, neither acidic nor basic.
- ✓ When finished, compare your predictions with your groupmates.

Laboratory (continuing)

B) Preparing the pH indicator based on red cabbage

- ✓ Chop 2 to 3 red cabbage leaves by hand.
- ✓ Add to the graal with 25 mL of hot water.
- ✓ Mash with the pestle until you obtain a dark purple extract.
- ✓ Filter using the funnel and filter paper.
- ✓ Set aside the extract.

C) Building the pH scales

- ✓ Place two rows with 5 micro test tubes each.
- ✓ Write down the pH values of 2, 5, 7, 10, 13 in each tube.
- ✓ Fill the tubes with 2 mL of each ready-made solution.
- ✓ Dip a pH indicator strip into each solution and compare it with the colour scale in the box.
- ✓ In the first row, place 2 mL of the red cabbage extract in each test tube – use the Pasteur pipette.
- ✓ In the second row, place 3 drops of the phenolphthalein pH indicator in each test tube.
- ✓ Write down all the results in a Table.

D) Testing pH test in various foods

- ✓ Separate 10 micro test tubes and label them with numbers 1 to 10 containing the foods to be tested.
- ✓ Testing should be done using any of the indicators chosen from the group along with juice or a mixture of the food with a small amount of water.
- ✓ Record the results in a Table.

Research and Conclusion

What types of pH indicators were used? Qualitative (information) or quantitative (number)?
What are the turning points (pH at which there is a colour change) of red cabbage and phenolphthalein?
Was the prediction you initially made about the pH of the food in the Fake News correct according to the results obtained?
What happened to the buffer solution when a strong base was added? Considering that blood is also a buffer solution, what would happen to the pH of our blood when we eat alkaline foods? And acidic foods?

Research which substances present in red cabbage and phenolphthalein work as pH indicators.
Research which substances present in each food tested are responsible for their acidic or basic/alkaline characteristics.

What incorrect scientific information was conveyed in the Fake News analysed? What is the impact of believing in it? How can it be combated?

The whole team planned the dissemination of the results (**Phase 4**, *October*) and evaluated the Project as a group and as individuals. The team choose three ways to communicate our findings (Figure 4): (a) to create an Instagram page (@meninas_fakenews) to post scientific information on COVID-19 and fighting FN (*November*); (b) to deliver a lecture and a workshop (*November*)

for the school community on how to identify information disorders and to use online fact-checkers; (c) to organise a local conference (*December*) to present the Project results and to conduct inquiry-based activities for other students.

We produced 22 posts on Instagram® with social media metrics: 192 followers, 1,223 likes, 235 shares and 202 comments. More than 200 people attended the lecture, workshop and conference during the Project. The students gave testimonials regarding the impact of the Project on their lives: "*The Project was wonderful, a great experience!*" (S1); "*The Project gave girls like me, who aren't very interested in Science, the opportunity to participate in such a surreal experience. It was an incredible initiative to encourage women to engage in this field. Unfortunately, opportunities like these are rare but very necessary*" (S2); "*I am extremely grateful and fulfilled because it was a wonderful and unforgettable experience. The best part was visiting UFF and meeting kind teachers. I hope you can carry out more projects like these in schools*" (S3). For the undergraduate student, "*It was a unique opportunity to take the lead in making decisions about a project and at the same time conduct teaching activities with high school students as a mentor"* (S4).

Figure 4: Students engaged in disseminating the Project findings through a lecture, a workshop, laboratory tests and a conference.



Final Remarks

The PAR "*Fighting Fake News in Science*" Project involved a multidisciplinary team of university academics and the local school community to build knowledge and insights on science-based FN about COVID-19. There is evidence of improving scientific literacy and media criticism through inquiry-based activities and social media scientific dissemination. Major limitations were found due to politically sensitive topics in a country psychologically shaken by threats to democracy and collective health. The Project ended in 2024, but its developments continue to be observed in new research, teaching and extension projects.

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Pre-service Primary Teachers Evaluate Media Sources On Climate Change

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The widespread dissemination of misinformation about climate change poses significant challenges for individuals, particularly non-experts such as pre-service primary teachers, in discerning reliable information. The present study explores the strategies employed by pre-service primary teachers to evaluate the credibility and validity of media sources related to climate change. Adopting a qualitative research design, a series of activities focusing on the recognition of deceptive tactics, the assessment of source expertise, and the understanding of media gatekeeping was developed and implemented in a form of a teaching experiment. Data was collected through audio-recorded sessions involving 14 pre-service primary teachers, working in groups of two. The findings revealed that while participants frequently emphasized source's reputation and background, they experienced difficulties in evaluating the relevance of authors' expertise and in considering the social aspects of science such as the role of scientific consensus. These findings highlight the need to integrate such aspects in initial teacher education programs in order to support the development of pre-service teachers' science media literacy.

Keywords: climate change, misinformation, science media literacy

Introduction

Climate Change Misinformation & The Need For Science Media Literacy

In recent years, there has been a growing international acceptance that climate change is one of the most urgent and challenging socioscientific issues due to its environmental, political, economic and social implications (IPCC, 2023; Leiserowitz et al., 2011). While the scientific community has reached a consensus regarding the scientific aspects of climate change and the role of anthropogenic activities in exacerbating the phenomenon, various controversial yet seemingly convincing information relating both the causes and the extent of climate change continues to be widely disseminated either through broadcast media or social media (e.g. IPCC, 2023; Leiserowitz et al., 2011). This kind of information often questions both the anthropogenic nature of climate change and the effectiveness, economic and political implications of the proposed response and adaptation measures (e.g. Whitmarsh et al., 2013).

Several interrelated factors explain why non-experts tend to believe or share such misinformation. These include cognitive dispositions that bias individuals' thinking, particularly their pre-existing beliefs, as well as social influences and online interactions that lead to isolated communities, commonly described as echo chambers or filter bubbles, which reinforce existing views and limit exposure to diverse perspectives. In addition, identity-protective thinking may lead individuals to accept misinformation that aligns with their cultural, political, or religious identities (e.g. Pimentel, 2025; Siani & Gennari, 2025). Finally, the systematic use of misinformation strategies *(deceptive tactics)* that cast doubt on well-established scientific findings, question relevant expertise and institutional credibility, emphasize scientific uncertainty, repeat false claims making them seem true *(illusory truth effect)*, and employ emotionally charged language (e.g. Lewandowsky et al., 2021) further reinforces non-experts' susceptibility to misinformation.

Within this context, tackling climate change misinformation requires a multifaceted approach. On the one hand, it involves policy initiatives and regulatory measures targeting online platforms, as well as adjustments in science communication and journalistic practices aimed at improving the quality of scientific information. On the other hand, it necessitates educational approaches that prepare individuals to critically evaluate scientific information encountered in the media. Focusing on this latter aspect, the need to equip non-experts with competencies for assessing the reliability and trustworthiness of information sources related to climate change becomes particularly relevant (e.g. Pimentel, 2025; Siani & Gennari, 2025; Osborne & Pimentel, 2023). The development of such competencies includes a. the understanding of epistemic dependance on experts and the role of empirical evidence in scientific processes; b. the interaction with media sources which involves skills and strategies for the identification of the source expertise, the identification of credible gatekeepers, the recognition of deceptive tactics; and c. the understanding of the role of personal pre-existing beliefs in the way individuals interpret information as well as the counter-balancing role of scientific consensus (e.g. Pimentel, 2025; Allchin, 2023; Osborne & Pimentel, 2023; Allchin, 2022; Höttecke & Allchin, 2020). Therefore, science education needs to emphasize the development of these competencies—commonly referred to as science media literacy—to effectively address and respond to the growing misinformation crisis related to contemporary socioscientific issues, such as climate change (e.g., Allchin, 2022; Höttecke & Allchin, 2020; Osborne & Pimentel, 2023).

Teachers' Science Media Literacy

With regard to teachers' evaluation strategies, recent research has highlighted a gap between teachers' digital skills and the depth of their information-evaluation practices. Although pre-service teachers frequently engage with online sources and demonstrate familiarity with digital tools, their evaluation of scientific information often remains superficial, focusing on surface-level indicators rather than epistemic or social - institutional features of science (e.g., Bellocchi et al., 2025). At the same time, there is limited empirical evidence on the specific strategies teachers employ when evaluating media sources related to socioscientific issues. The literature therefore underscores the need to enrich initial teacher education with science media literacy–oriented approaches, so that teachers can develop robust evaluation practices and gradually transfer these competencies to science classrooms (e.g., Fernández-Carro et al., 2024).

Based on the above, the purpose of the present study is to explore the way pre-service primary teachers interact with and evaluate media sources regarding contemporary socioscientific issues such as climate change. Hence, the research question that leads the present study is *"What strategies do pre-service primary teachers employ in order to evaluate media sources regarding climate change?"*.

Methods

Participants

The participants of the study were 14 pre-service primary teachers (PPTs) who were in the second year of a 4-year bachelor degree in primary education. The participants had attended a compulsory course on fundamental concepts of physics as well as a course on fundamental principles of science education. The participants were divided into seven groups.

The Teaching Experiment

In the present study, the teaching experiment method was employed, which is an interview organized as a learning situation (Komorek & Duit, 2004). This method is particularly appropriate

for exploratory studies, as it allows researchers to examine participants' reasoning processes as they unfold during engagement with the learning activities. The teaching experiment was structured in five phases. Initially, pre-service primary teachers (PPTs) engaged in an introductory activity designed to elicit their prior criteria for evaluating media sources. The subsequent phases emphasized (i) the recognition of deceptive tactics, (ii) the evaluation of credibility across different media gatekeeping mechanisms, and (iii) the assessment of source expertise (Allchin, 2022; Allchin, 2023; Höttecke & Allchin, 2020). In the final phase, participants applied these competencies to support evidence-based reasoning and decision-making in a new authentic situation.

The teaching experiment was implemented through the development of five learning activities. The instructional context involved a renewable energy source company accused of providing deceptive data regarding the level of carbon dioxide emissions associated with its products. Within this scenario, the company's lawyer had access to a variety of information sources and was required to decide which sources could be used to build company's defense strategy. PPTs were asked to assume the role of the lawyer's assistants and were responsible for evaluating the credibility and validity of the available sources. The content of each activity is described below:

Activity 1. PPTs Orientation & Engagement

PPTs are presented with four snapshots of media sources (a scientific report, an online newspaper, a blog post, and an Instagram post) (Figure 1) addressing climate change and are asked to rank the sources in order of increasing validity, explicitly mentioning the criteria used.

Figure 1. Snapshots of media sources.



(a) Scientific report



(b) Online newspaper



(c) Blog post



(d) Instagram post

Activity 2. PPTs Familiarization With Common Deceptive Tactics

PPTs are provided with an article and a rubric outlining five common deceptive tactics and are asked to identify whether these tactics are present in the text. The aim for PPTs is to categorize the article as a high or low quality source and to justify whether it should be considered credible evidence in the case.

Activity 3. PPTs Familiarization With Review Mechanisms

PPTs are initially presented with three different media sources (an academic paper, an online newspaper, and an Instagram post) communicating the same information by the same author and are asked to comment on the validity of each source. Subsequently, PPTs discuss the mediation of professional gatekeepers across different media types and rank the sources in order of increasing validity to determine which source should be provided to the court.

Activity 4. Ppts Familiarization With Criteria For Assessing Source Expertise.

PPTs are presented with five cards describing different source profiles based on educational background, professional and academic experience, participation in organizations and institutions, and other relevant responsibilities. PPTs are asked to select the most suitable profile to trust in relation to a renewable energy source dilemma and to justify whether this source should be presented to the court. Additionally, PPTs are asked to reflect on what further information they would require in order to finalize their decision.

Activity 5. Application Of Knowledge And Skills To A New Context.

PPTs are provided with an authentic TikTok video featuring a scientist expressing views on renewable energy sources. PPTs are asked to decide whether the source should be trusted and used as evidence in court, providing justification for their decision.

Data Collection And Analysis

The teaching experiment was conducted during one 90 – minute session for each group of participants and data was collected accordingly through audio recordings of each session.

Due to the exploratory nature of the study, qualitative methods of content analysis were used (Bryman, 2017). The category system developed to analyse the criteria employed by PPTs when evaluating media sources is presented in Table 1 and includes six broad categories: (i) source expertise, (ii) source features, (iii) source motivations, (iv) source attitude towards science, (v) source communication strategies, and (vi) source interface.

Table 1. Categorization of evaluation criteria.

Categories	**Subcategories**
Source expertise	Status
	Background & expertise
	Credentials & reputation
Source features	Review mechanisms
	References
	Authenticity
Source motivations	Conflicts of interests
	Purpose of the source
Source attitude towards science	Questioning of scientists & formal institutions
	Alignment with scientific consensus
	Scientific uncertainty
	Illustration of empirical data
Source communication strategies	Use of emotional language
	Illusory truth effect
Source interface	Web domain
	Layout

Results

With regard to the results of the study, data analysis revealed that PPTs predominantly refer to source expertise when evaluating a media source related to climate change as well as to the source

features and attitude towards science. In contrast, references to source motivations such as conflicts of interests or communication strategies including the use of emotional language, were less often. Finally, it seems that the technical characteristics of online sources do not constitute a primary criterion in PPTs' source evaluation strategies. The following table (Table 2) presents the absolute frequencies of PPTs' references to the different evaluation criteria.

Table 2. Results regarding PPTs evaluation criteria.

Categories	Subcategories	References	Total
Source expertise	Status	35	123
	Background & expertise	43	
	Credentials & reputation	45	
Source features	Review mechanisms	48	78
	References	23	
	Authenticity	7	
Source motivations	Conflicts of interests	13	44
	Purpose of the source	31	
Source attitude towards science	Questioning of scientists & formal institutions	24	76
	Alignment with scientific consensus	10	
	Scientific uncertainty	10	
	Illustration of empirical data	32	
Source communication strategies	Use of emotional language	24	30
	Illusory truth effect	6	
Source interface	Web domain	7	12
	Layout	5	

By focusing on source expertise, PPTs tended to emphasize the source's credentials, such as their collaborations, the reputation of their home institutions, and the source's educational background or professional experience. For instance, one PPT noted: *"He {the source} has a PhD and he is now working at a well-known institution while he has recently published three papers. So, I think that this profile is the most reliable one"*. Interestingly, source status alone was sometimes considered sufficient for establishing validity, even without mentioning specific background or experience. For example, one pre-service teacher mentioned: *"She is a researcher, and we unquestioningly trust researchers and scientists"*. Thus, although PPTs frequently referred to source expertise, closer examination of their reasoning suggests that such references often relied on indicators of scientific status or authority rather than on the relevance of expertise to the issue under examination.

Concerning source features, PPTs mainly highlight the review mechanisms employed in different media sources, such as peer review or editorial review. For instance, one PPT explained: *"In scientific reports or academic papers, there is a scientific committee responsible for checking the research process, whereas on platforms like Instagram or TikTok, no one verifies what is published—anyone can share their views and beliefs"*.

Regarding sources' attitude toward science, PPTs often emphasized that the illustration of empirical data - such as diagrams or data visualizations - enhances a source's perceived validity. Less frequently, they recognized that questioning scientists or the broader scientific consensus is an indicator of reduced credibility. For instance, one PPT noted: *"Here, I think that he casts doubt on something that nine out of ten scientists have agreed on. So, I think that I won't take this source into account"*.

The findings reported here illustrate the ways in which PPTs evaluated media sources related to climate change.

Discussion And Conclusions

Based on the study findings, PPTs seem to apply credibility criteria that have been identified in the literature when evaluating media sources on climate change and they are generally able to distinguish between high- and low-quality sources (e.g. Pimentel, 2025; Allchin, 2023; Osborne & Pimentel, 2023). In particular, PPTs tend to rely heavily on source expertise - a finding consistent with recent empirical research involving pre-service science teachers in Australia (e.g. Bellochi et al., 2025) - as well as on the presence of review mechanisms and the use of empirical data representations. However, relying solely on diagrams, numerical data and tables may be misleading for PPTs, since such elements can mirror the structure of professional scientific reports without necessarily reflecting robust scientific practices (e.g. Allchin, 2022; Pimentel, 2025). From a science media literacy perspective, this fact highlights the importance of moving beyond surface indicators of credibility toward evaluation strategies that take into account how scientific knowledge is produced and validated. Additionally, the emphasis placed on a source's status indicates that PPTs tend to accept scientific authority, without considering whether a scientist's expertise is directly relevant to the issue under examination – an aspect widely recognized as crucial in the evaluation of scientific information. Finally, PPTs rarely identified or even tried to identify potential source conflicts of interests, and they paid limited attention to the role of scientific consensus when assessing the credibility of information. These findings suggest limited familiarity with the social-institutional aspects of science, which are central to informed evaluation of socioscientific information (e.g., Pimentel, 2025; Erduran & Dagher, 2014) and suggest that PPTs approach source evaluation primarily through indicators that are associated with scientific authority and credibility of an individual source rather than broader scientific processes.

In conclusion, the present findings highlight key areas for supporting PPTs' development of science media literacy competencies. In particular, teacher education programs could place greater emphasis on the social and institutional dimensions of science, such as the role of scientific consensus, conflicts of interest, and the relevance of expertise to a specific scientific or socioscientific issues, in order to strengthen PPTs' science media literacy. Accordingly, future work may focus on the design, development, and evaluation of teaching resources informed by these insights, as well as on further examination of how to support the development of more robust evaluation strategies among PPTs and how such competencies are transferred to classroom practice.

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The Deep Structure For Teaching And Learning Socioscientific Issues

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The present theoretical contribution proposes a comprehensible framework for teachers who wish to integrate socioscientific issues (SSI) into their science classes. To this end, we conduct a theoretical argumentation that demonstrates a relationship between visions of scientific literacy and competencies for teaching and learning science through SSI. Following this, we discuss possible approaches to teaching SSI and emphasize the need for a theoretical foundation in collective pedagogical content knowledge for SSI. Our approach involves combining learning objectives and teaching structures to promote moral development in students working with SSI, based on existing theoretical models. The connection between learning and teaching is facilitated by the combination of so-called 'basis-models', which aim to foster communication and assessment competencies. By structuring science classes in this way, teachers can be empowered to effectively manage a scaffolding of lessons. This enables teachers to clarify their role in enabling argumentations and promoting students' moral development within SSI.

Keywords: SSI, moral-development, basis-models

Introduction

The modern world is undergoing a transformative era marked by profound changes in sociopolitical, economic, and environmental spheres, as well as in the established social order. These aspects are interrelated, often controversial, and require complex analysis for comprehensive understanding. When included in science classes, topics such as climate change are referred to a socioscientific issues (SSI). SSI are defined as "the deliberate use of scientific topics that require students to engage in dialogue, discussion, and debate" (Zeidler & Nichols, 2009, p. 49). Engaging in argumentation and discourse on SSI should promote the development of critical assessment competencies, as decision-making is heavily influenced by the abundance of both accurate and misleading information. As a result, the significance of SSI in education has grown (Chen & Xiao, 2021). Some national curriculum standards have already incorporated explicit topics, such as climate change (Guerrero & Sjöström, 2024). Given these contemporary and essential demands, it is crucial to focus on the role of teachers, who must guide students in navigating and engaging in complex argumentation and discourse. Although there is a considerable amount of research and educational materials on SSI, a comprehensive theoretical pedagogical framework is still lacking (Viehmann et al., 2024). To address this gap, we propose integrating an established learning-teaching model into the discussion — the basis-model-theory (Oser & Baeriswyl, 2001) — and applying it to SSI. Building on this model, we develop a theoretical framework that is grounded in the deep structures of learning and teaching processes aimed at fostering students' moral development while addressing SSI.

Aim: Developing A Theoretical Approach

In this contribution, we aim to address the following question: Which deep structures underpin the learning and teaching of socioscientific issues? To explore this question, we implement a theoretical approach by using an accessible syllogism:

- First premise: Learning about SSI involves recognizing a dilemma, using criteria to argumentatively address the dilemma, and perceiving the resulting moral development.

- Second premise: Moral development requires teaching SSI, where planning includes learning objectives, appropriate content that can be acquired through self-regulation, and well-guided interactions.
- Conclusion: Teaching SSI should encourage learners to develop their moral understanding in relation to a dilemma. Through moderation and self-regulation, learners are able to formulate arguments. Development is perceived through teacher-learner interactions. The combination of two so-called basis models (Oser & Baeriswyl, 2001) provides the scaffolding for teaching and subsequently learning SSI.

First Premise: Learning Through SSI Promotes Moral Development

There is an apparent consensus regarding the main learning goal of science education in school, which is defined by the term '*scientific literacy*'. This refers to the knowledge of science that should empower individuals to solve problems within scientific domains, facilitate critical thinking, and enable participation in complex discussions about technology and sustainability. The definitions provided by Roberts for scientific literacy form a basis of these widely accepted understandings (Roberts, 2007, p. 766). Chen and Xiao noted that despite this consensus, the concept of scientific literacy has been interpreted differently within the national curriculum standards of various countries (Chen & Xiao, 2021, p. 11).

In their examination of the connection between scientific literacy and SSI, Valladares and Sjöström reviewed the interpretations and visions of scientific literacy, emphasizing the need for developing learning objectives. These range from "Vision I," which relates to traditional content-based teaching, through "Vision II," which involves applying science to SSI contexts, to "Vision III," where science facilitates engagement in action and transformation (Sjöström, 2024; Valladares, 2021). Such engagement could be understood as an externalization of acquired argumentation and evaluation competencies. In summary, learners should become competent outsiders, especially in today's era of misinformation (Osborne & Pimentel, 2023).

Recently, the concept of '*science identity*' has been developed from the previous construct of scientific literacy, as a parallel dimension to ‘scientific knowledge’ and the ‘competencies’ (OECD, 2023). This relatively new concept aims to evaluate young people's connection to science. Within this dimension, one sub-dimension explicitly considers environmental awareness and the integration of personal and scientific values applicable to SSI contexts, as defined in the PISA framework (ibid.). These concerns should be incorporated into critical decision-making processes and sustainable practices.

In addition, Kashyap (2026) recognizes the relationship between science identity and scientific literacy, proposing a pathway that links the two. According to Kashyap, science identity can grow into scientific literacy through the “capacity to adopt meta-positions” and the “awareness of the dialogical self” (ibid., p. 12). His approach involves developing the concept of literacy as the coordination of “value-laden and socially consequential” concepts within a dialogical competence (ibid., p. 18).

In our case, in Germany, the discourse on science literacy does not play a predominant role, but rather the competencies that show similarities, such us the ability of using scientific knowledge for decision making (Kauertz et al., 2012). The term ‘*competencies*’ refers to Weinert’s definition, which involves long-term learning processes that address “cognitive and (in many cases) motivational, ethical, volitional, and/or social components” (Weinert, 2001, p. 62). Over the past decade, science competencies have been operationalized into standards divided into four competency areas: content knowledge, scientific enquiry, communication and assessment (i.e. evaluation) (Neumann et al., 2010).

The new national educational standards explicitly include interdisciplinary objectives in communication and assessment areas, which can be contextualized with reference to SSI (*KMK*, 2024). In these contexts, students must navigate various criteria based on scientific and personal perspectives to formulate well-grounded arguments that lead to decisions and subsequent reflections on consequences (ibid.). Such argumentations are shown to play a central role as a vehicle for reasoned claims, a view accepted internationally (Dawson & Carson, 2017). For this aim, students must learn how to construct an argument, identify and select criteria, and apply them accurately in language. The abilities involved are part of communication competence. Beyond those skills, students must also evaluate dilemmas and develop well-reasoned personal viewpoints on interdisciplinary topics. Furthermore, when making decisions, they connect their competence with their performance (Blömeke et al., 2015). This process is closely linked to assessment competence and is similar to a form of "functional scientific literacy" (Zeidler & Sadler, 2023, p. 920).

As they evolve their personal beliefs through these evaluation processes, it can be assumed they undergo moral development (Oser & Baeriswyl, 2001), as defined by the theory of moral development (Kohlberg & Hersh, 1977). Zeidler adds, in this context, the term of moral inquiry, as "an activity aimed at advancing virtue when confronted with conflicting or unclear moral judgements" (Zeidler, 2024, p. 41). Moral inquiry can be addressed through controversial SSI after creating an ethical disequilibrium that awakens "empathy, sympathy, and compassion" (ibid., p. 40). Furthermore, an "empathetic dissonance" is necessary to trigger a motivational response (ibid., p. 47). In this way, learners can develop their morality by engaging in dilemma discussions that facilitate the realization of context-related moral reasoning through both cognitive and motivational dimensions (Nunner-Winkler, 2007). Immersive experiences, such as place-based SSI instruction, promote conceptual and moral development in students (Herman et al., 2021).

Second Premise: Teaching SSI Requires The Involvement Of Morality

Regarding pedagogical structures for dealing with SSI, Saunders and Rennie developed a model for ethical inquiry, which they investigated qualitatively with a small sample of teachers (Saunders & Rennie, 2013). The model proposes nine sequential stages: "(1) teacher preparation, (2) students engaging with the broad issue, (3) students understanding the science behind the issue, (4) individual reflection on the issue/values exploration, (5) group discussion of specific issues, (6) deciding on specific questions or controversial statements, (7) ethical thinking about the questions or statements from various ethical frameworks, (8) ethical decision-making and justification, (9) action/evaluation/decision" (ibid., p. 270). Teachers highlighted that the model demonstrates cohesiveness and flexibility and aids students in critical thinking. The study emphasized the need to develop pedagogies that move away from transmissive approaches, advocating for teachers to guide students' self-regulated research and debates. To achieve this, "teachers may require assistance in developing criteria that support them in assessing issues where there are no right or wrong answers" (cf. ibid., p. 269). In this noteworthy approach, the need for argumentative moral development is also recognized.

Macalalag et al. (Macalalag et al., 2020; Johnson et al., 2020; Minken et al., 2021) developed, implemented, and investigated a professional development course for teaching SSI in STEM classes, which considers the following steps: "(A) Identifying the issue, (B) Scientific phenomenon, (C) Engage in STEM modeling, (D) Consider issue system dynamics, (E) Employ reflective scientific scepticism , (F) Compare and contrast multiple perspectives, (G) Elucidate own position / solution" (Minken et al., 2021, p. 123). The study showed that the participant teachers increased their knowledge and instructional skills regarding SSI. However, they

demonstrated lower levels of content knowledge related to the SSI and of scientific scepticism (ibid.).

The results of Macalalag et al.'s study are consistent with Bayram-Jacobs et al. (2019). In Bayram-Jacobs et al.'s research, teachers learned to adapt SSI materials in a professional development course. In that study, all materials used the same scaffolding: "Presenting a dilemma, recap or learn scientific knowledge needed for the task, and a student's SSI task which is a simple, structured activity to resolve the dilemma" (ibid., p. 1213).

Both Macalalag and Bayram's theoretical background resides in PCK. Building on the theoretical approach of Magnusson et al. (1999), the presented studies qualitatively illuminate some interactions between the components of PCK for teaching SSI: "Knowledge of Instructional Strategies for Teaching SSI, Knowledge of assessment of SSI, Knowledge of curriculum, Knowledge of learning context, and Knowledge of students' SSI learning" (Chang & Park, 2020, p. 425).

A final model, called Values and Knowledge Education, combines the mentioned perspectives in a very complete approach that aimed at solving dilemma situations: "(0) Preparation of the students and pupils, (1) Introduce dilemma, (2) First decision, (3) First arguments, (4) Exchange experience and asking about missing information, (5) Looking for evidence, (6) Exchange information, (7) Second arguments (dilemma discussion), (8) Synthesis of information, (9) Repeat 4 through 8 if necessary, (10) General synthesis, (11) Generalization" (Patry & Weyringer, 2022, p. 29). Studies conducted using this framework demonstrate positive development of transformative processes by participants (ibid.).

In Germany, a group of science educators from different science education disciplines with a focus on assessment competence, has presented a model comprising six stages: (1) Perceiving, (2) Analysing, (3) Arguing, (4) Weighing, (5) Deciding, (6) Reflecting (Langlet et al., 2022). Each stage is further divided into several substages, except for the last one. The publication also provides useful exercises and tips, such as separating steps into three types of implementations: to perceive and analyse; to argue; and to weigh, decide and reflect. Once again, the progression of arguments, decisions, and reflections occurs in clearly defined steps, supporting the moral development of students.

Finally, research has shown that interdisciplinary collaboration among teachers in schools is an effective way to develop interdisciplinary content and establish pedagogical knowledge of SSI, thereby promoting the intended moral development through argumentation (Kutluca, 2021; Viehmann et al., 2024).

Conclusion: Bringing Teaching And Learning Together Through Deep Structures

A Selection Of 'Basis-Models' For Designing The Deep Structure

As highlighted in the previous paragraphs, moral development can be identified as the fundamental learning objective for students engaging with SSI. Moreover, fostering moral development in science classes demands teaching plans that ensure effective communication and assessment, particularly in the context of SSI. Both, assertions and recognized needs require a theoretical approach that depicts the deep structures of learning and teaching SSI, with a clear emphasis on promoting moral development.

Oser and Baeriswyl proposed a theory of 12 so-called basis-models for the deep structure design of teaching processes, drawing on psychological and educational theories (Oser & Baeriswyl, 2001). These basis-models are derived from diverse learning objective types and consist of

various steps of teaching and learning that form chains. The theory does not allow any steps to be skipped or omitted. In addition, basis-models can be combined sequentially or interwoven. Research has shown that planning lessons using a selection of three basis-models ('Concept Building', 'Learning Through Discovery', and 'Problem Solving') can enhance students' learning outcomes in science classrooms (Geller et al., 2014). However, basis-models for the competency areas of communication and assessment have not been sufficiently investigated and are not included in this selection, as they target developmental processes beyond content-based or inquiry learning (Hümbert-Schnurr et al., 2022). Instead, they aim to foster multi-perspective, valid arguments, as discussed in the previous paragraphs.

An analysis of the remaining nine basis-models reveals that competencies concerning assessment and communication can be enhanced through different learning objective types and corresponding choreographies. Two of these models are particularly well-suited because their learning goal types are similar to those of SSI (Oser & Baeriswyl, 2001, p. 1046):

- "Development as the Aim of Education" (DAE), with the learning goal type "deep structure transformation, such as moral judgment" in five steps.
- "Hypertext Learning" (HL), with the learning goal type "reordering and revaluing information bits" in six steps.

The basis-models DAE and HL can be combined as follows to achieve the learning objectives described in the right column of Table 1b. Starting from the corresponding steps, the resulting learning processes foster engagement with conflicts (DAE1) and exploration of positions in complex contexts (DAE2). During the self-regulated phase (DAE3), students search for information independently or in groups to support arguments. Oser predicted moral development in this step (ibid.). Subsequently, with teacher moderation, students analyse and weigh these arguments (DAE4). The process culminates in reflection on personal development (DAE5), which contributes to moral development. The HL basis-model can be introduced in the step (DAE3) if the lesson also focuses on critical thinking, for example. In that case, students must first select the topic (HL1), then structure the information (HL2), define the objectives (HL3) and determine their learning approach (HL4). After that, they execute the self-determined path (HL5) and, finally, they manage the results (HL6).

Comparison Of Models

The presented combination of basis-models reflects the fundamental characteristic of our approach, which underscores the deep structure. The following tables illustrate this characteristic by comparing the stages outlined by Saunders & Rennie, Macalalag et al., Patry & Weyringer and Langlet et al. (as presented above) with those of our own approach.

Table 1a. Comparison of first two approaches presented in this contribution.

	Saunders & Rennie	Macalalag et al.
(-)	(1) Teacher preparation	
(I)	(2) Students engaging with the issue	(A) Identifying the issue
(II)	(3) students understanding the science behind the issue	
(III)	(4) individual reflection on the issue/values exploration (5) group discussion of specific issues (6) deciding on specific questions or controversial statements	(B) Scientific phenomenon (C) Engage in STEM modeling (D) Consider issue system dynamics
(IV)	(7) ethical thinking about the questions or statements from various ethical frameworks (8) ethical decision-making and justification	(E) Employ reflective scientific skepticism (F) Compare and contrast multiple perspectives
(V)	(9) action/evaluation/decision	(G) Elucidate own position / solution

Table 1b. Comparison of following two approaches and our own.

	Patry & Weyringer	Langlet et al.	Our Approach
(-)	(0) Preparation of students		
(I)	(1) Introduce dilemma	(1) Perceiving	1. Dilemma presentation (DAE1)
(II)	(2) First decision	(2) Analizing	2. Exploring controversial positions (DAE2)
(III)	(3) First arguments (4) Exchange experience and asking about missing information (5) Looking for evidence (6) Exchange information	(3) Arguing	3. Exposure to advance arguments (DAE3) 1. Topic selection (HL 1) 2. Structuring information (HL2) 3. Defining objectives (HL3) 4. Learning approach (HL4) 5. Path execution (HL5) 6. Result management (HL6)
(IV)	(7) Second arguments (dilemma discussion) (8) Synthesis of information (9) Repeat (4)-(8) if necessary	(4) Weighing	4. Argument Analysis (DAE4)
(V)	(10) General synthesis (11) Generalization	(5) Deciding (6) Reflecting	5. Reflection (DAE5)

The selection and combination of basis models reveal an underlying structure for planning and analysing teaching sequences for SSI. Additionally, this approach's coherence with others has been emphasized. One strength of the present approach is its simple, user-friendly structure, which supports learning processes. Furthermore, rather than providing a solution to a dilemma, these learning processes encourage investigation and debate surrounding it. Therefore, fostering communication and assessment competence should be a long-term process that incorporates similar strategies and deep structures in several SSI lessons on different topics. Furthermore, the selected basis models focus on the self-regulated development of students' science identities and beliefs, which teachers moderate. As shown above, this is a starting point for moral inquiry. In conclusion, this approach explicitly fosters interactions between at least three components of SSI-PCK: knowledge of instructional strategies for teaching SSI, knowledge of the learning context, and knowledge of students' SSI learning.

Limitations, Future Direction, And Conclusion

One difficulty when working with the basis-models is that the functions of the different steps may be misunderstood (Krabbe et al., 2015). In this case, it is important to explicitly define the stages of the deep structure applied to SSI and develop materials based on the proposed guidelines. This would allow for the extrapolation of the SSI framework to a smaller order of magnitude.

Additionally, when considering the practical implementation of controversial debates, developing teaching strategies for scaffolding in the last two steps presented in Table 1b (right column) seems necessary. In this context, the basis-model 'Learning Through Realistic Discourses' could be considered for the deep structure of these learning and teaching processes.

Understanding the underlying deep structures of teaching and learning, as proposed in our approach, is essential for identifying better future research directions in the field of SSI. The selected basis-models are based on psychological and pedagogical research and consider the development of students' knowledge and morality. They are also more process-oriented than product-oriented, making them more coherent with the desired competencies and activities.

The present approach could make SSI more practical for teachers due to its simple structure, which makes planning single science lessons easier, for example. However, future empirical analyses of existing SSI materials, as well as the development of new materials, are necessary. These materials could then be used in professional development programs for pre-service and in-service teachers. The effectiveness of these training courses should be studied.

For science teachers, this knowledge could provide with insight into managing SSI processes, enabling them to motivate students to move away from transmissive pedagogies and facilitate personal growth.

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Socioscientific Issues And Laboratory Work In Lower Secondary School - Some Challenges

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Previous research suggests socioscientific issues (SSI) can improve student interest in science, increase learning of content and strengthen scientific literacy. Most of this research, however, is focused on the level of the teaching unit. There is relatively less on how different activities within the teaching units suit an SSI approach. In this study we investigate the teaching and impacts of a module focused on food production and population growth in lower secondary school (age 15). We employ a mixed-methods design, combining classroom observation and interview with a pre-post difference-in-differences design. Quantitative results (n=3876) are promising with medium-sized effects on situational interest and content specific self-efficacy. Qualitative results based on 90 hours of observation and interviews with students and teachers, however, indicate that socio scientific issues work well with non-experimental activities, but less so with experimental lab activities. The laboratory parts of the module tend to be more focused on proving the usefulness of suggested solutions than on allowing students to investigate their own hypotheses. This has consequences for the depth of discussions and limits the types of evidence it is possible to bring forward by students. We suggest that this reflects not only limitations in the design of the module but also points to broader challenges in integrating student laboratory work within SSI-based teaching, particularly for younger students.

Keywords: Socioscientific Issues, Laboratory Work in Science, Secondary School

Introduction

Socioscientific issues (SSI) are ill-structured problems with no simple solutions that involve political, ethical, social aspects as well as scientific knowledge. They are often controversial and contentious issues for society, requiring the use of evidence from science as well as other disciplines, and often include a debate between students about possible ways of action, moral reasoning and judgement (Evagorou & Nielsen, 2019; Evagorou & Dillon, 2020; Tidemand & Nielsen, 2017). SSIs can be based on dilemmas from many domains such as environmental sustainability (e.g. ecological systems, food production), resources and energy (e.g. clean energy development), technology (e.g. artificial intelligence and large language models), medicine and neurosciences (e.g. gene therapy) (Evagorou & Nielsen, 2019; Wan & Bi, 2018).

Previous research has suggested the use of socioscientific issues in science education can promote student interest in science, increase learning of content, as well as their scientific literacy. On this basis, many scholars have argued for the integration of SSI into science teaching (Sadler & Dawson, 2012; Çalik & Wiyarsi, 2024). At the same time, the literature highlights a number of challenges associated with SSI-based teaching, including resistance to pedagogical innovation, the inherent complexity of the topics, and the demand for specialized teacher training (Tidemand & Nielsen, 2017; Zeidler & Sadler 2023; Ke, Sangori, Sadler & Friedrichsen 2020).

In recent years, empirical research on socioscientific issues (SSI) has expanded considerably. However, much of this literature has focused on analysing the effectiveness of complete teaching units or instructional sequences, rather than examining the role of individual activities within those units. As a result, comparatively little research has addressed how specific classroom

activities are designed and how well they align with the principles of SSI-based teaching, particularly at educational levels below upper secondary or tertiary education (see e.g. Sadler, 2004; Sadler & Dawson, 2012; Çalik & Wiyarsi, 2024; Zeidler & Sadler, 2023; Nolan & Zeidler, 2025; Karisan et al., 2018; Sá-Pinto et al., 2022). Moreover, relatively few studies have investigated how younger students engage with the SSI approach and different types of activities, such as experimental laboratory work, within such a framework (Evagorou & Nielsen, 2019).

To address these gaps, the present study examines how fifteen-year-old students in lower secondary school engage with and make sense of classroom activities within an SSI-based teaching module. By focusing on classroom processes during implementation, the study provides a more fine-grained understanding of how SSI-oriented activities function for younger students across different activity types. The following research questions guided the study:

- In what ways do lower secondary students participate in an SSI-based teaching module?
- How do experimental laboratory activities and non-experimental activities function within an SSI-based teaching approach?

Research Method And Data

The study is based on a mixed-methods approach combining classroom observation and interviews with a pre-post difference-in-differences design based on survey data from students. Although this paper draws on the quantitative part of the study for necessary context and background, this paper primarily is concerned with data from the qualitative component.

The module under study consists of a five-week in-school activity followed by a one-day out-of-school activity for some classes. The module integrates content from physics/chemistry, geography, and biology.

The approach in the quantitative component of the study is reported elsewhere (Bergquist & Osmundsen, in press). The qualitative component is based on case studies of eight lower secondary school classes in which the module was implemented. Cases were selected using a maximum-variation sampling strategy to support analytical transferability, based on criteria such as teacher experience and school socio-economic context. Qualitative data collection took place during the first part of the 2023/24 school year (August–December 2023).

The SSI framework served as an explicit analytical lens throughout the qualitative study. Prior to classroom data collection, a desk study of the module's learning materials was conducted, during which all activities were analysed against key characteristics of SSI-based teaching, including the extent to which activities foregrounded socioscientific problems, supported student deliberation, and facilitated discussion of the possibilities and limitations of scientific and technological solutions. This analysis informed both the observation focus and the subsequent interpretation of classroom practices.

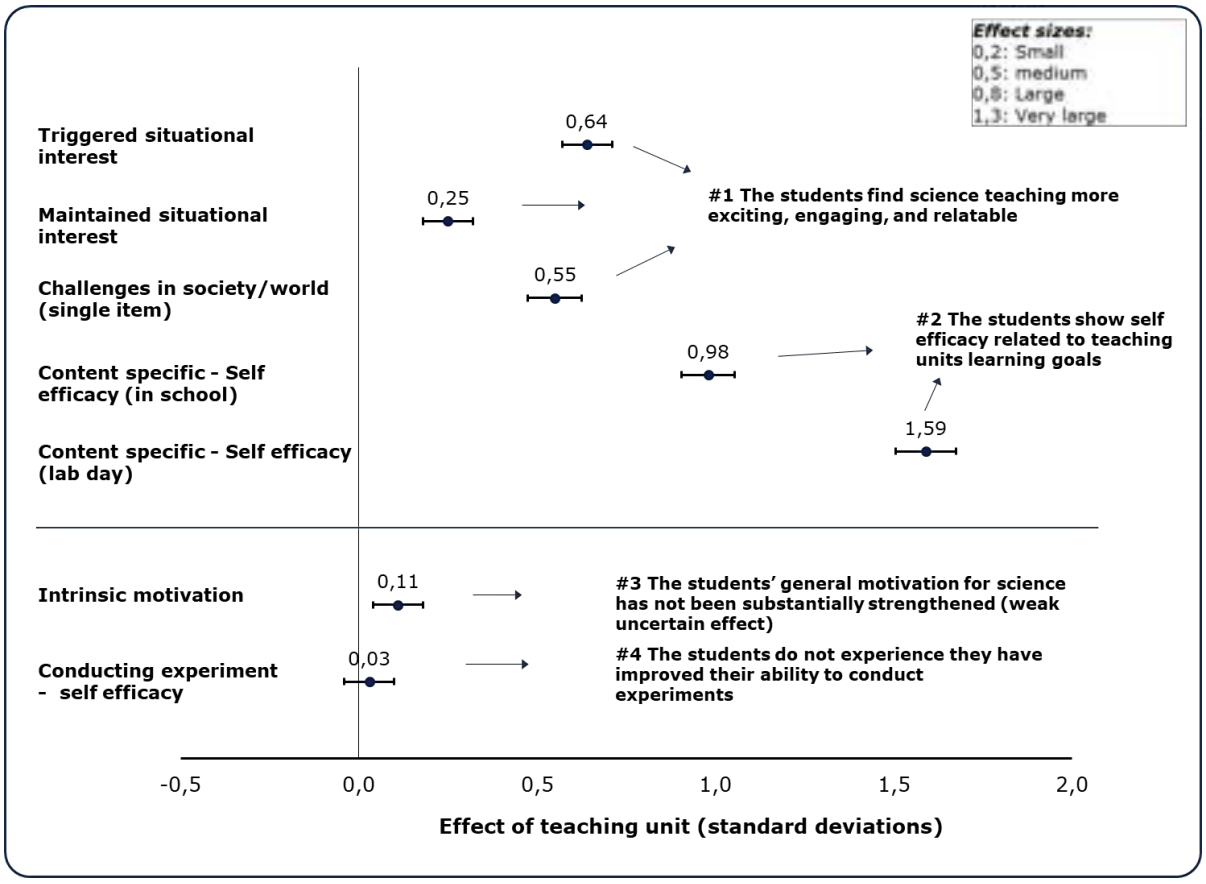
The main body of qualitative data consists of approximately 90 hours of naturalistic classroom observation across the eight cases. During observations, detailed field notes were taken and subsequently transcribed. In addition, focus group interviews were conducted with 3–5 students in each class at selected points during the course and with one focus group per class at the conclusion of the module. Students were selected to capture a range of perspectives, including variation in engagement with the module.

Finally, semi-structured interviews were conducted with each of the eight participating teachers at the end of the course to elicit their reflections on implementing the SSI-based module. All interviews were audio-recorded and transcribed verbatim.

Findings

Figure 1 shows the results of the quantitative part of the study.

Figure 1. Impacts on student interest, motivation and self-efficacy.



Note: Standardized effect estimates from regression models, with cluster-robust standard errors at the class level. Lines indicate 95% confidence intervals around point estimates (n=3,876 observations).
Source: Bergquist and Osmundsen (in press)

Results showed improved student interest and self-efficacy. Students who were taught the module were more interested in and showed a greater desire to participate, compared to students in the control group (Triggered situational interest, medium effect: 0.64 SD) (see Figure 1). Additionally, students found that the teaching unit could be related to daily lives to a high degree. (Sustained situational interest, small effect: 0.25 SD) With regards societal or global challenges, there was a medium effect (0.55 SD).

However, the results also showed that there was only a weak uncertain effect on intrinsic motivation for science (0,11 SD) and that it didn't improve their ability to conduct experiments (se Figure 1).

These largely positive results are supported by the qualitative results; however, they also show a more nuanced picture. The module consists of many different teaching activities that can roughly be divided into two groups: non-experimental and experimental activities. All of the latter take place in a laboratory setting. We observe a marked difference in student engagement in the non-experimental and experimental activities.

A non-experimental activity that figures prominently in the module is a turn-based game, where the students develop a fictitious country. In each round, they invest within four categories: agriculture, fertilizer, education and behaviour. As they have limited resources, they must prioritize their investments. After each turn, they can see the consequences of their choices for the country's food needs, food production, CO2 emissions and school attendance. In their

prioritization, they must use knowledge about the country's demography, climate and soil conditions, which they know from a previous activity. The game gives the students a lot of autonomy as there is no 'right answer' and students truly get the opportunity to investigate and select solutions to deal with the socioscientific issue.

We see that students participate in the game with an exploratory approach, for example by studying data about the population and climate of the country while discussing investments. We also see students trying to figure out which real country their fictional country most likely resembles and then research everything about that country to strengthen their actions in the game. Furthermore, we see that students engage in arguments with each other for and against different investments from each other. For example, they relate to scientific evidence when they discuss possibilities and limitations of investments and to their consequences for the economy, climate, environment and people. This behaviour shows that the students at the same time have an exploratory, independent and creative approach and can relate to the socioscientific issue. A teacher describes the link between the game and the socio-scientific issue like this: *"The game is clearly the one activity who make the students aware of factors that you have to take into account: Why can't you just make sure that now we make investments that give lots of food? That won't solve the problem. It just results in more population growth and even greater food needs".* In addition to working competently with the problem, students work with commitment. Even if the game is very simple in design, the students identify with the country they are playing. As one student puts it: "*It's a great responsibility to be responsible for the development of a whole country. And we're only 15 years old!".*

The module also includes several experimental lab activities. In these activities the students show less engagement and less competence compared with the gaming activity. Examples of experimental lab activities include when students examine properties of catalytic reactions, as catalysis is part of the production of artificial fertilizers, which is one of the possible solutions to increase food production. They investigate, via hypothesis formation and variable control, how much nutrient is leached from the soil of their fictitious country when crops are exposed to chemical fertilizers. Both these activities are closed-ended with a fixed protocol that the students must follow.

We see that the students in the experimental lab activities participate in a results-oriented way, with a focus on solving the task 'correctly' and finding 'the right answer'. We also see uncertainty among students, as they often seek the teacher's confirmation as to whether they are on the right path. We don't see indications of the students connecting their work in the experimental lab activities with the problems or the challenges of their fictional country. The students' commitment and participation are directed towards the lab work itself, and reflection on results is not linked to the problem or to what they can use their results for in relation to the development of their countries. Nor do they reflect on how what they have investigated relates to the production or use of chemical fertilizers. As one teacher puts it: "*It is quite demanding for the students to succeed with the lab activities, and this puts the socioscientific issue in the background".* At the same time, we also noticed that the teachers rarely made explicit connections between the experimental laboratory activities and the socioscientific issue or the students' fictional countries.

Discussion

In conclusion, we find that non-experimental activities generally support the intentions of SSI-based teaching, whereas experimental laboratory activities appear less successful in this regard, suggesting a possible challenge in SSI-based teaching. We argue that this is not only due to limitations in the design of the module under study but also points to broader challenges in integrating student laboratory work within SSI-based teaching, particularly for younger students.

These challenges may be related to safety considerations and students' limited laboratory competencies, which are often associated with age and maturity in lower secondary school. As a result, meaningful laboratory activities can be difficult to design in ways that allow students sufficient autonomy to explore and evaluate different solutions. Consequently, experimental laboratory activities tend to be relatively close-ended, with fixed protocols for students to follow, which may conflict with key principles of socioscientific issues. Rather than enabling students to explore alternative solutions experimentally, laboratory work often focuses on confirming the solution proposed in the module or by the teacher. This finding has broader implications for the integration of SSI-based teaching alongside traditional science education, as many curricula emphasise not only data collection and analysis but also students' engagement with laboratory work.

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Argument Development Through Socioscientific Issue-Based Teaching: Asteroid Mining With Gifted Students

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This study examines how socioscientific issue-based instruction supports the argument development processes of gifted secondary school students. The research was conducted within the context of asteroid mining, a contemporary socioscientific topic that encompasses scientific, ethical, and societal dimensions. The teaching process was structured based on the Socioscientific Issues Teaching Framework developed by Friedrichsen et al. (2016). The activities were enriched in line with Renzulli's (2014) Triple Enrichment Model to support the cognitive and affective characteristics of gifted students. Furthermore, socioscientific dilemma cards, developed based on Yacoubian's (2015) Critical Thinking and Nature of Science Framework, were used to deepen students' critical thinking and awareness of the nature of science. The research was conducted using a case study design, adopting a qualitative research approach. The study group consisted of 30 gifted secondary school students studying at a Science and Art Centre in Turkey. The implementation process lasted six weeks and consisted of four main activities. The data sources were written arguments developed by the students; the data were examined through descriptive analysis, taking into account the structural characteristics of the arguments. The findings show that the arguments developed by the students can be grouped into three levels: simple, advanced, and complex. It was determined that a significant proportion of the students demonstrated reasoned thinking skills, but the number of students developing complex arguments was limited. The results reveal that socioscientific issue-based instruction supports gifted students in developing arguments by evaluating scientific, ethical, and social dimensions together; however, it also highlights the need for explicit and structured argumentation instruction to develop more complex argumentation skills.

Keywords: argumentation, asteroid mining, gifted students

Introduction

Today, rapid, complex and often unpredictable developments in science and technology mean that it is no longer sufficient for individuals to simply possess knowledge of scientific concepts (Hodson, 2011). Instead, it is becoming increasingly critical for individuals to be able to evaluate this knowledge within social, ethical, political, and economic contexts (Jasanoff, 2004; OECD, 2018). The increasing visibility of the social consequences of scientific knowledge production necessitates a rethinking of the aims of science education (Sadler, 2004). In this context, one of the fundamental goals of science education is to ensure that students are not merely consumers of knowledge but grow into individuals who can make reasoned and informed decisions about complex, controversial, and uncertain scientific issues (Sadler, 2011; Zeidler, 2014).

Socioscientific issues, which lie at the intersection of scientific knowledge and social values and inherently involve uncertainty, ethical dilemmas, and multiple perspectives, provide a strong pedagogical context for this goal (Sadler & Zeidler, 2005; Zeidler et al., 2009). These topics reveal that scientific knowledge is not a fixed, unchanging and indisputable structure, but rather a value-laden process negotiated within social contexts (Kolstø, 2001; Sadler, 2004). In this respect, socioscientific issues enable students to develop a more critical and realistic understanding of the nature of science (Lederman, 2007; Yacoubian, 2015).

Socioscientific issue-based teaching is an approach that aims to holistically develop students' critical thinking, scientific reasoning, and argumentation skills, and it is gaining increasing attention in the field of science education (Evagorou & Osborne, 2013; Zeidler et al., 2009). This approach seeks to transform students from passive recipients of information into active participants who evaluate scientific evidence, consider opposing views, and develop reasoned arguments (Sadler et al., 2007). Research shows that teaching processes conducted in socioscientific contexts strengthen students' ability to relate scientific knowledge to everyday problems and increase their motivation to learn (Aikenhead, 2006; Ratcliffe & Grace, 2003).

Argumentation is a fundamental scientific practice that involves individuals defending their claims with evidence, evaluating alternative views, and reaching reasoned conclusions (Kuhn, 1991; Toulmin, 1958). In the context of science education, argumentation is recognised as a central learning practice that makes students' scientific thinking processes visible and encourages critical evaluation (Erduran et al., 2004; Sampson & Clark, 2008). Numerous studies have demonstrated that argumentation-based learning environments deepen students' conceptual understanding and support their scientific reasoning skills (Berland & Reiser, 2009; Osborne et al., 2004).

Argumentation-based learning environments, particularly for gifted students, offer significant opportunities for supporting higher-order cognitive skills and deep thinking (VanTassel-Baska, 2013; Zohar & Dori, 2003). These students have the potential to evaluate multiple perspectives, think abstractly, and engage in critical inquiry when faced with complex problems (Renzulli, 2014; VanTassel-Baska, 2013). However, for this potential to emerge, learning environments must be consciously structured and students must be guided towards active intellectual production (Subotnik et al., 2011).

Space mining, and asteroid mining in particular, has emerged as a contemporary socioscientific topic in recent years, drawing attention for its scientific, economic, and political dimensions (Cockell, 2011; Sonter, 1997). Asteroid mining encompasses numerous controversial elements, such as the sustainable use of natural resources, space law, technological limitations, global economic inequalities, and ethical responsibilities (Elvis, 2014; Milligan & Schwartz, 2020). This multidimensional structure makes addressing the topic in the context of science education pedagogically meaningful (Sadler, 2011; Zeidler et al., 2005).

With these characteristics, asteroid mining provides a rich learning context that enables students to discuss not only the question of ‘what is possible?’ but also ‘what should be done?’ (Sadler, 2011; Zeidler & Nichols, 2009). This context supports students in questioning the limits of scientific knowledge, the societal consequences of scientific progress, and value-based decision-making processes (Osborne et al., 2004).

The main aim of this study is to examine how socioscientific issue-based teaching conducted in the context of asteroid mining reflects on the argument development processes of gifted students. In this regard, the main research question is formulated as follows:

RQ1. How do gifted students participating in a socioscientific issue-based learning environment develop arguments regarding a controversial socioscientific issue such as asteroid mining?

Within the scope of this question, the structural characteristics, levels of complexity, and perspectives contained in the arguments developed by the students are examined.

Theoretical Framework

This study is built upon three fundamental theoretical pillars: the teaching approach to socioscientific topics, argumentation, and the education of gifted students. These three theoretical

areas provide a holistic teaching approach that supports students' reasoned thinking about controversial scientific issues, evaluation of multiple perspectives, and scientific decision-making processes (Erduran et al., 2004; Sadler, 2004; Zeidler et al., 2011).

The socioscientific issues teaching approach argues that scientific knowledge cannot be considered independently of its social, ethical, and political contexts and aims to engage students in active reasoning processes within these contexts (Sadler, 2004; Zeidler et al., 2011). Due to their inherent uncertainty, value conflicts, and multiple perspectives, socioscientific issues require students not only to learn scientific concepts but also to evaluate this knowledge alongside its societal consequences (Kolstø, 2001; Sadler & Zeidler, 2005). With these characteristics, socioscientific issues contribute to the development of a more critical and realistic understanding of the nature of science (Lederman, 2007; Yacoubian, 2015).

The Socioscientific Issues Teaching Framework developed by Friedrichsen et al. (2016) proposes that teaching such topics should holistically address context creation, scientific content, ethical and social dimensions, and students' reasoning processes. This framework enables students to position scientific knowledge not merely as content to be conveyed, but as a type of knowledge that is discussed and negotiated in social contexts (Friedrichsen et al., 2016; Sadler et al., 2007). Based on this theoretical framework, socioscientific dilemma cards were developed using Yacoubian's (2015) framework of Critical Thinking and Nature of Science Framework. These cards are designed to clearly highlight epistemological uncertainty, value-laden decision-making processes, and the evaluation of evidence in socioscientific contexts. Through structured dilemmas that encourage students to reason, compare alternative perspectives, and reflect on the nature and limitations of scientific knowledge, the aim is to support students' participation in informed and critical reasoning processes.

Argumentation is defined as a fundamental scientific practice that involves individuals defending their claims with evidence, evaluating alternative views, and reaching reasoned conclusions (Kuhn, 1991; Toulmin, 1958). Toulmin's argument model, with its structure consisting of claim, evidence, reason, supporting evidence, qualifier, and counterclaim components, is widely used in science education research to make students' thinking processes visible (Erduran et al., 2004; Sampson & Clark, 2008). Numerous empirical studies have demonstrated that argumentation-based learning environments support students' conceptual understanding, scientific reasoning, and critical thinking skills (Berland & Reiser, 2009; Osborne et al., 2004).

Argumentation processes conducted in sociological contexts enable students to reason not only based on scientific evidence but also by considering ethical, economic, and social values (Sadler & Zeidler, 2005; Zeidler & Nichols, 2009). In this respect, argumentation stands out as a thinking and learning practice suited to the multidimensional nature of socioscientific issues (Sadler, 2011).

The education of gifted students requires enriched, cognitively demanding, and flexible learning environments that support these students' high levels of curiosity, creativity, and problem solving potential (Renzulli, 2014; VanTassel-Baska, 2013). In this study, the teaching process was structured in line with the Triple Enrichment Model developed by Renzulli (2014). This model aims to deepen students' areas of interest, encourage higher-order thinking skills, and support them in producing original work (Renzulli, 2014; Subotnik et al., 2011).

The integration of socioscientific topics and argumentation-based activities with the Triple Enrichment Model provides a powerful learning environment that activates gifted students' cognitive depth, creativity, and task awareness (VanTassel-Baska, 2013; Zohar & Dori, 2003). This integrated structure supports students not only in producing knowledge but also in critically

questioning it and reconstructing it from different perspectives (Sadler, 2011; Subotnik et al., 2011).

Methodology

This research was conducted using a qualitative research approach with a case study design (Merriam, 2009; Yin, 2018). The case study provides a method suitable for the purpose of this research, as it allows for an in-depth examination of teaching practices conducted within a specific context (Yin, 2018).

The study group consists of gifted secondary school students enrolled at the Science and Art Centre. These Centres are supportive educational institutions affiliated with the Ministry of National Education in Turkey. They aim to identify the individual talents of gifted students continuing their formal education at an early age and to develop their scientific, artistic, and cognitive potential through enriched programmes (Ministry of National Education [MoNE], 2016). The implementation process lasted six weeks and consisted of four main activities, spanning a total of six class hours. The activities were structured in line with socioscientific subject-based teaching principles and designed to encourage students to engage in active discussion and argumentation (Friedrichsen et al., 2016). In the final activity, discussions were held on ethical, economic, and social dimensions using socioscientific dilemma cards based on Yacoubian's (2015) framework of critical thinking and the nature of science.

The activities carried out during the implementation process were structured to support students in gradually developing arguments within the context of socioscientific issues and are described in Table 1.

Table 1. Activities Implemented During the Instructional Process.

Activity	Description of the Activity	Pedagogical Purpose
Activity 1: Asteroid Modeling	Students created physical models to elicit their prior knowledge about the concept of asteroids.	To activate students' prior knowledge and foster affective engagement with the topic
Activity 2: Concept introduction of asteroid mining	The scientific and technological aspects of asteroid mining were explored.	To promote engagement with scientific content and awareness of diverse perspectives
Activity 3: Modeling of Metal Composition	The metals potentially found in asteroids and their possible uses were modeled.	To support the use of scientific evidence and reasoned thinking
Activity 4: Socioscientific Dilemma Cards	Discussions were conducted using dilemmas addressing ethical, economic, and societal dimensions.	To enable students to develop arguments by considering multiple perspectives

The data were examined through descriptive analysis, taking into account the structural characteristics of the arguments (Erduran et al., 2004).

Findings

In this study, the arguments developed by gifted students in the context of asteroid mining were analysed, taking into account their structural characteristics and levels of complexity. During the

analysis process, the students' arguments were classified into three levels: simple, advanced, and complex, using the Toulmin-based argumentation approach (Erduran et al., 2004; Toulmin, 1958).

The findings reveal that a significant proportion of students demonstrated reasoned thinking skills in a socioscientific context. However, these skills varied in terms of argumentation complexity. This classification of arguments into levels is consistent with the developmental progression proposed in the argumentation literature (Erduran et al., 2004; Kuhn, 1991). The distribution of argument types developed by students is presented in Table 2.

Table 2. Types of Arguments Developed by Students.

Argument Level	Frequency	General Characteristics of the Arguments
Simple Arguments	12	Arguments based on a single claim, containing limited justification, and primarily focusing on the potential benefits of asteroid mining
Advanced Arguments	11	Arguments incorporating scientific concepts and concrete examples, but including counterarguments to a limited extent
Complex Arguments	7	Arguments that integrate multiple perspectives, acknowledge potential limitations, and address ethical dimensions, demonstrating a high level of justification

Table 2 shows that students developed arguments most frequently at the basic and advanced levels. The fact that arguments at the basic level were mostly structured around a single claim and contained limited justification suggests that students initially approached the socioscientific topic superficially. This situation is consistent with previous studies showing that students initially evaluate socioscientific issues in a benefit-consequence-oriented manner (Sadler & Zeidler, 2005; Zeidler et al., 2009).

In advanced-level arguments, it was observed that students used scientific concepts more consciously and attempted to support their claims with specific examples and explanations. These findings parallel research showing that socioscientific issue-based learning environments support students' deeper engagement with scientific content (Evagorou & Osborne, 2013; Osborne et al., 2004).

Although complex-level arguments were developed by a more limited number of students, it was determined that these arguments addressed multiple perspectives, ethical concerns, and possible limitations together. Such arguments demonstrate that students incorporate not only scientific knowledge but also value-based reasoning into the process. This points to the potential of socioscientific issues to develop students' reasoning skills that take into account ethical and social dimensions (Sadler, 2011; Zeidler et al., 2011).

Discussion And Conclusion

The findings of this study reveal that socioscientific issue-based teaching meaningfully supports gifted students' argument development skills. The fact that a significant proportion of students moved from simple claim-based explanations to more structured and reasoned arguments confirm the role of socioscientific contexts in promoting scientific reasoning (Sadler, 2004; Zeidler et al.,

2009). This finding is consistent with studies arguing that socioscientific topics move students away from being passive recipients of information and towards active intellectual engagement (Aikenhead, 2006; Ratcliffe & Grace, 2003).

However, the relatively limited number of students developing arguments at a complex level indicates that some components of argumentation require more explicit and structured instruction. In particular, the limited use of higher-level argumentation elements such as refutation, the use of qualifying statements, and the systematic handling of counterarguments is a situation that has also been emphasised in previous argumentation studies (Erduran et al., 2004; Kuhn, 1991; Sampson & Clark, 2008).

From a pedagogical perspective, it can be said that socioscientific issue-based teaching has the potential to activate gifted students' multidimensional thinking skills. The use of a current and controversial topic such as asteroid mining has facilitated students' ability to relate scientific knowledge to ethical and social contexts. This aligns with studies arguing that socioscientific topics bridge learning with real-world problems (Sadler, 2011; Zeidler & Nichols, 2009).

Consequently, this study demonstrates that socioscientific issue-based instruction supports gifted students' argument development processes. Future research should examine how instructional designs that include longer-term applications, explicit argumentation instruction, and structured peer interaction affect students' ability to develop complex and multidimensional arguments (Mercer, 2000; Sampson & Clark, 2008).

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Connecting The Dots: Quassr Scores And S^{3}R Profiles In Preservice Teachers' Socio-Scientific Scenarios

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This study is aimed to explore the relationship between preservice science teachers' (PSTs) socio-scientific reasoning (SSR) levels, evaluated through the Quantitative Assessment of Socio-scientific Reasoning (QuASSR), and their Socio-scientific Sustainability Reasoning (S^{3}R) profiles through self-generated socio-scientific scenarios. A sample of eight PSTs created scenarios addressing a variety of complex socio-scientific issues. The research included qualitative analysis based on the S^{3}R model framework to examine these scenarios. Quantitative results indicated that PSTs showed medium SSR levels, with notable strengths in the perspective-taking dimension and limitations in scepticism . However, scenarios produced by PSTs with lower inquiry scores demonstrated strong S^{3}R profiles, excelling in components such as problematization and values. However, these lower inquiry participants showed deficiencies in the knowledge and governance dimensions compared to their higher inquiry. These findings illustrate a qualitative correlation between SSR and S^{3}R profiles, accompanied by a quantitative discrepancy, particularly in the inquiry dimension. This discrepancy highlights the need for further exploration of measurement methodologies pertaining to the inquiry dimension within SSR assessments. The study contributes to the expanding literature on SSR by illuminating the complex interplay between quantitative and qualitative evaluations. It also offers crucial insights that may inform the development of effective pedagogical strategies aimed at enhancing the SSR skills of future science educators, thereby supporting their capacity to engage with contemporary societal issues critically and thoughtfully. Through this research, it is aimed to advance understanding of how different dimensions of reasoning can coexist and develop within preservice teacher education.

Keywords: Pre-Service Teacher Education, Qualitative Research, Science Education

Introduction

Socio-scientific issues (SSIs) are complex, controversial topics that require individuals to integrate scientific knowledge with social, ethical, and personal values to make informed decisions (Zeidler et al., 2005). SSR is usually viewed as a multidimensional construct, comprised of complexity, inquiry, perspective-taking and scepticism dimensions (Romine et al., 2017). Complexity reveals that SSIs cannot be addressed with singular and simple solutions due to the multi-layered structure of issues. Perspective-taking indicates that different stakeholders involved in SSI topics can develop different but contextually valid solution proposals in line with their individual priorities, beliefs, and prejudices. Inquiry emphasizes that SSIs involve numerous questions awaiting answers in both scientific and social contexts and therefore require a continuous process of research and debate. Scepticism requires careful selection of information sources related to these issues; it necessitates questioning whether sources are biased and whether the data presented is reliable (Sadler et al., 2007) Together, these dimensions indicate how well individuals can apply scientific understanding and reasoning within the context of SSIs while integrating relevant social and ethical considerations. It is especially important for preservice science teachers to develop strong SSR skills, because their reasoning practices will influence the framing, discussion, and negotiation of socio-scientific issues in future classrooms.

Developing socio-scientific reasoning (SSR) skills is crucial for citizens to effectively engage in contemporary societal challenges such as climate change, genetic engineering, and energy production (Sadler et al., 2007). Assessing PSTs' SSR through self-generated SSI scenarios

provides a valuable window into their understanding and application of these complex concepts (Ekborg et al., 2009). By creating their own scenarios, PSTs demonstrate their ability to identify and analyse key issues, consider different perspectives, and integrate scientific knowledge with ethical and social considerations.

The Quantitative Assessment of Socio-Scientific Reasoning (QuASSR) is a well-established instrument for measuring scientific reasoning skills (Romine et al., 2017). However, it primarily focuses on assessing SSR based on given cases. It is limited in its capacity to analyse discourse or other student-generated artifacts like SSI scenarios. In contrast, the Socio-scientific Sustainability Reasoning (S^3R) model offers a structured rubric for examining reasoning across multiple dimensions in student-generated artifacts, including collectively produced texts and self-generated socio-scientific scenarios (Morin et al., 2014). Focusing on student-generated artifacts through qualitative analysis makes it possible to examine how individuals define socio-scientific problems, develop and justify arguments, draw on scientific and contextual knowledge, and deal with uncertainty within these issues. The S^3R framework includes six interrelated components: problematization, interactions, knowledges, uncertainties and risks, values, and governance. Problematization focuses on recognizing the multidimensional structure inherent in the process of addressing an issue and understanding that the problem cannot be confined to a simple framework. Interactions emphasize awareness of the mutual relationships between components within dynamic systems and the complexity created by these relationships. Knowledges focus on how different sources of knowledge (experiential, social, local, etc.) are brought together and related to academic knowledge. Uncertainties and risks involve approaching claims of knowledge with caution, accepting that knowledge is contextual, and expressing scepticism at the epistemological level. Values focus on the explicit articulation of value-based attitudes and the justification of these attitudes. Governance addresses how regulatory mechanisms offer opportunities for citizen participation in the process of balancing different interests. S^3R model provides a valuable rubric for assessing various levels of reasoning in different dimensions in student-generated artifacts (collective text on wikis) (Morin et al., 2014).

This study investigates the relationship between QuASSR-assessed SSR levels and S^3R profiles in PSTs' scenario development. By analysing the scenarios developed by preservice teachers, we examined how their socio-scientific SSR skills, as measured by QuASSR, relate to their S^3R profiles. This research will contribute to a deeper understanding of the multifaceted nature of SSR and provides valuable insights into developing practical pedagogical approaches that foster SSR skills in future science educators. Our research question is as follows:

> What is the relationship between QuASSR-assessed SSR levels and S^3R profiles in pre-service science teachers' socioscientific scenario development?

This study will contribute to a growing body of research on SSR by exploring the interplay between quantitative and qualitative assessments. By examining the relationship between QuASSR scores and S^3R profiles, we can better understand the factors that contribute to effective SSR in future science educators.

Methods

The participants of the study consisted of 8 pre-service science teachers (PSTs) (1 male, 7 female). There were 12 participants at the beginning; however, 4 of them was removed from the study as their scenarios did not have characteristics of SSI. They did either not have any conflict or not include science. Within the scope of the 'Socio-scientific Issues in Science Teaching' elective course, quantitative data were obtained from the PSTs using the QUASSR (Quantitative Assessment of Socio-scientific Reasoning) scale, and qualitative data were obtained by asking

them to create a socio-scientific scenario. In the scope of the course, the nature of SSI were discussed in the first week. In the second week the PSTs were asked to fill in the QUASSR test. Then based on what they learned about the nature of SSI and the example scenarios they read in QUASSR test, they were asked to create their own scenarios. They were allowed to select any topic they were interested, either any topic they are experiencing or witnessing or any hypothetical topic they were expecting to be an issue in the future. Then, they were given time to make research to create their scenarios. The limited number of participants was suitable for the qualitative approach of this study, since the goal was to conduct a detailed examination centered on the reasoning patterns demonstrated through self-generated socio-scientific scenarios.

The QUASSR scale developed by Romine, Sadler, and Kinslow (2017) includes two socio-scientific cases (Hydraulic Fracking at Pavilion Wyoming and Branville Bay) with 11 two-stage questions each. These are related to the four sub-dimensions of socio-scientific reasoning (SSR): complexity (4 questions), inquiry (6 questions), perspective-taking (4 questions), and scepticism (6 questions). The Cronbach alpha reliability coefficient of the scale was calculated as 0.79 by Romine et al. (2017) and 0.82 by Irmak (2020), who adapted it into Turkish. The data from the QUASSR scale was analysed in line with the framework proposed by Romine et al. (2017). According to this framework, 0 represents low-level, 1 represents medium-level, and 2 represents high-level SSR. The average score for each SSR dimension for each PSTs were calculated using IBM SPSS software. Then, the PSTs were grouped as low-level and high-level SSR based on their QUASSR scores. PSTs having less than the mean score of the group were categorized as low-level SSR while the rest were categorized as high-level SSR group.

The scenarios were analysed according to the S^3R (socio-scientific sustainability reasoning) model consisting of 6 components (problematization, interactions, knowledges, uncertainties and risks, values and governance) with the help of the rubric developed by Morin et al. (2014). Radar charts were drawn for S^3R profiles of two SSR level groups. Radar charts were applied as a visual analytic to describe the relative distribution of S^3R components between groups, and to compare the overall reasoning profiles. To ensure the trustworthiness of the study, different data collection methods were used, and the findings were interpreted together (triangulation). In addition, 35% of the scenarios created by the PSTs were analysed by both researchers, and the inter-coder reliability was calculated 0.83 (acceptable value) using the consensus/(agreement+disagreement) formula proposed by Miles and Huberman (1994).

Results

Table 1. SSR Scores of PSTs.

Participants	Complexity	Inquiry	Scepticism	Perspective-Taking	Total SSR
PST_1	1,25	1,17	0,33	1	0,9
PST_2	0,75	1,33	1,5	1	1,2
PST_3	1,5	0.83	1,67	1,25	1,3
PST_4	1,5	1,17	1,83	2	1,6
PST_5	0,5	1.67	0	1	0,8
PST_6	1,25	1,25	0,17	1,5	1
PST_7	1,5	1,5	1,33	1,5	1,25
PST_8	1,5	1,5	1	2	1,6
Mean	1,22	1,29	0.98	1,41	1,21

PSTs SSR scores ranged from 0.98 to 1.41 with a mean of 1.21 indicating medium SSR. The lowest mean score was found in scepticism dimension (M=0.98) and highest in perspective taking dimension (M=1.41), which is similar to the result of Irmak (2020). These findings suggest that PSTs generally demonstrate moderate level of SSR, which varies across different dimensions. SSR and S^3R scores of the PSTs are provided in Table 1 and Table 2.

When PSTs scenarios were inspected, it was realized that their selected topics were about various topics: climate change (2), gene therapy (2), pharmacology, space research, genetically modified foods, and cosmetics. An example scenario (PST_4) about food capsules (GMF) can be given as follows:

> "In the future, as humanity's resources decrease, scientists have developed a hunger-relieving capsule. This capsule provides the nutrients that a person needs, leading to a change in food production. Not feeling hungry all-day results in increased productivity and resource savings, which are among the advantages of this capsule.
>
> However, just as any scientific development has advantages, it also has disadvantages. The effects of this capsule will be of the nature of a medicine, and like any medicine, they will have negative side effects that will affect people. Furthermore, this capsule may be addictive. Uncontrolled use will harm human health. Lastly, it reduces socialization because eating food is a social activity. People who use the capsule in just one sip will become more dependent on the easily accessible hunger-relieving capsule."

PSTs' scenario texts were analysed based on S^3R model. Their highest values were found in problematization dimension (M=2,63) while the lowest dimensions were knowledge (M=1) and uncertainties and risks (M=1,13).

Table 2. S^3R Scores of PSTs.

Participants	Problematization	Interactions	Knowledges	Uncertainties and Risks	Values	Governance
PST_1	3	3	1	1	2	3
PST_2	2	2	1	1	2	3
PST_3	3	2	1	2	3	2
PST_4	4	2	1	1	3	1
PST_5	1	1	1	1	2	1
PST_6	2	1	1	1	2	1
PST_7	3	2	1	1	3	2
PST_8	3	3	1	1	3	3
Mean	2,63	2	1	1,13	2,5	2

Based on S^3R scores radar charts were generated to illustrate the profiles of PSTs with different SSR levels. Each axis of the radar chart represents a component of the S^3R framework: Problematization, Interactions, Knowledges, Uncertainties, Values, and Governance. The distance of each line from the centre indicates the level of each component within the S^3R profile.

As in Figure 1, participants with higher SSR total scores (average of all dimensions together) tend to demonstrate stronger S^3R capabilities across all dimensions. This suggests that a strong foundation in SSR is crucial for developing a holistic understanding of complex SSI.

In Figure 2, each radar chart represents the S3R profiles of the PSTs grouped by their performance on a specific dimension of the QuASSR instrument (Complexity, Perspective Taking, Inquiry, and Scepticism). When the radar chats created for four dimensions of SSR differently, some

inconsistencies with the one drawn based on SSR total scores are seen. While the overall trend was evident, notable inconsistencies emerged when examining the specific dimension of inquiry. Low-inquiry group's scenarios were assessed to be better in terms of most of the aspects of S^3R except for interactions and knowledges.

Figure 1. S^3R Profile of PSTs based on SSR Total Scores.

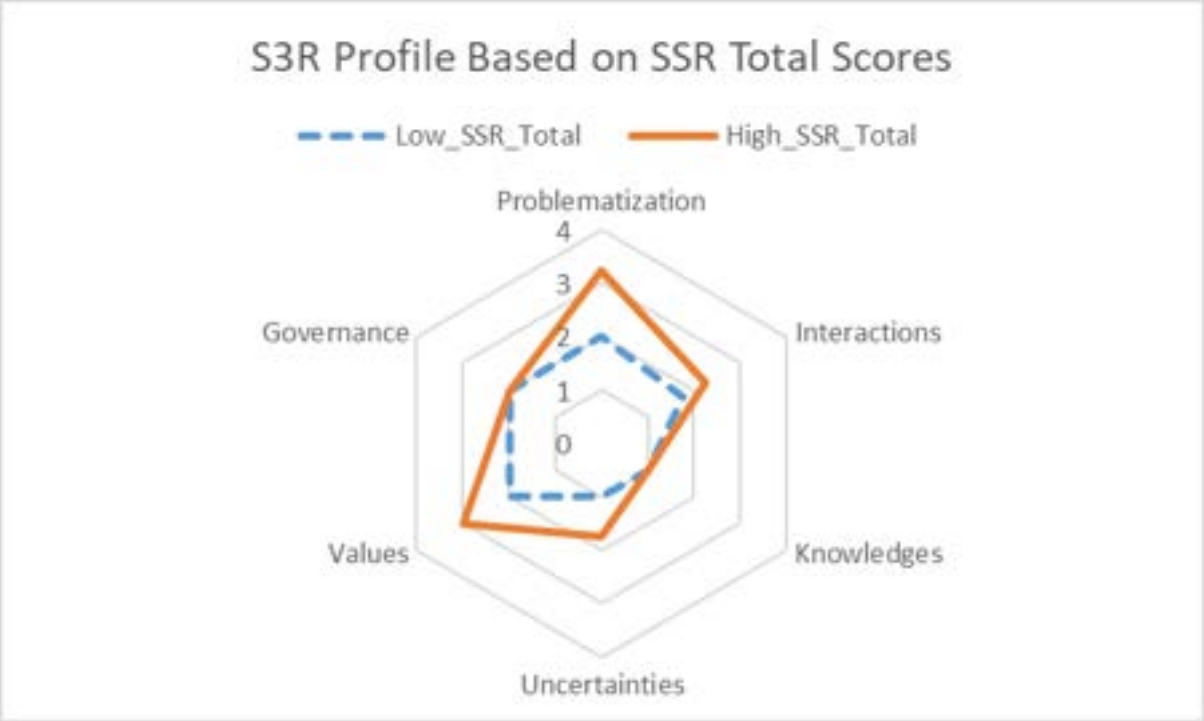


Figure 2. S^3R Profile of PSTs based on Different Dimensions of SSR.



The inquiry dimension of SSR refers to understanding that there are many questions that need to be answered scientifically and socially in SSIs and that SSIs are open to continuous research in the scientific and social field, feeling the need to ask more questions and research more new information in the discussion of SSIs (Romine et al., 2017). Therefore, the radar charts indicated

that contrary to other SSR skills, inquiry is not an indicator of high-quality scenarios in terms of reasoning.

Discussion

This study investigated the relationship between QuASSR-assessed SSR levels and S^3R profiles in preservice science teachers. While the findings suggest a positive correlation between higher QuASSR scores and stronger S3R profiles, the study also highlights the limitations of relying solely on quantitative measures like the QuASSR to fully capture the multifaceted nature of SSR In particular, the results for the inquiry dimension suggest that quantitatively assessed SSR skills do not always align with the quality of reasoning evident in self-generated socio-scientific scenarios. Quantitative methods often fail to adequately capture the social, institutional, and relational contexts that shape values and reasoning (Morris, 1991). The QuASSR, for example, may not fully account for the diverse social and cultural backgrounds of the PSTs, which can significantly influence their perspectives on SSI. Conducting a qualified reasoning and interpretation process regarding SSI requires individuals to have a certain level of mastery over the relevant topics. In this context, selecting topics that individuals are familiar with in terms of knowledge and experience in studies addressing SSI will yield more reliable results (Tüzüngüç, Doğan & Han Tosunoğlu, 2021). However, in scenario-based and quantitative measurement tools such as QuASSR, differences in PSTs' prior knowledge of the scenario under consideration may cause the measured levels of SSR to be affected by scenario-specific knowledge gaps. This situation carries the risk that findings obtained with QuASSR may reflect PSTs' mastery of the scenario topic rather than their actual reasoning abilities, limiting the scale's use as a context independent assessment tool. Additionally, the focus on standardized questions may have overlooked the richness of qualitative data, such as personal experiences, interpretations, and emotional responses, which are crucial for understanding the complexities of SSR. Self-generated scenarios analysed through the S^3R framework help make these implicit aspects of reasoning more appearent. As noted in the QuASSR validation process, inconsistencies across different scenarios highlight the potential for biases and limitations in quantitative assessments (Romine et al., 2017). Conversely, while qualitative methods can provide deeper insights into SSR, they may lack the generalizability and precision that quantitative approaches offer. A balanced integration of both methodologies could enhance the assessment of SSR, allowing for a more comprehensive understanding of this complex construct. In addition, these findings indicate that quantitative and qualitative approaches address different aspects of SSR.

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Unlocking Perspectives: Exploring Initial Design Principles Of Culture-Based Socio-Scientific Issues Training For Indonesian Pre-Service Biology Teachers

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In the last two decades, socio-scientific issues (SSIs) have been crucial in advancing scientific literacy. Students' socio-cultural backgrounds need to be considered in SSI-based education because cultural beliefs might influence their initial knowledge and guide their decision-making. SSIs require competent teachers, so it is important to introduce SSI-based education to pre-service biology teachers (PBTs), especially in Indonesia, which is known for its diverse subcultures and has limited research on SSIs. Currently, limited research examines how PBTs incorporate students' socio-cultural backgrounds when designing their CBSSIs classes. A deeper understanding of Indonesian lecturers and PBTs' perspectives is needed to understand how to develop a CBSSIs training programme for Indonesian PBTs to strengthen their skills in helping students navigate the complexity of science and culture. In developing the training programme, understanding the current landscape in teaching and learning SSIs and CBSSIs in the Indonesian context and the needs and aspirations of the CBSSIs training programme from lecturers' and PBTs' perspectives is needed. Semi-structured interviews were used to explore these perspectives. The results showed that teaching and learning SSIs is not done explicitly. Lecturers and PBTs shared their needs and aspirations for the training programme. Based on the results, five initial design principles (IDPs) were extracted to develop the training programme, which are (a) Understanding SSIs/CBSSIs, (b) Experiential Learning, (c) Collaboration and Reflection, (d) Accommodating Third Space, and (e) Theory and Practice. This work provides a basis for science educators on what principles to use when introducing CBSSIs to pre-service teachers.

Keywords: pre-service teacher education; teacher preparation; sociocultural perspectives; cultural diversity; socio-scientific issues

Introduction

In the last two decades, socio-scientific issues (SSIs) have been crucial in advancing scientific literacy. Ratcliffe and Grace (2003, p. 1) defined SSIs as "any issue which has a basis in science and has a potentially large impact on society". In SSI-based education, students' socio-cultural backgrounds need to be considered (Zeidler & Kahn, 2014) because cultural beliefs might influence their initial knowledge and guide their decision-making (Wahono et al., 2021). However, Ladachart and Ladachart (2021) argue that teaching SSIs using cultural contexts, also known as Culture-Based Socio-Scientific Issues (CBSSIs), is mainly uncommon. Nelson and Braff (2020, p. 6) define culture as "a set of beliefs, practices, and symbols that are learned and shared". Since teaching SSIs requires competent teachers (Subiantoro et al., 2021), and the success of navigating from everyday life to science classrooms and vice versa depends on the teachers (Aikenhead & Jegede, 1999), it is important to introduce SSI-based education to pre-service biology teachers (PBTs).

Currently, limited research, if any, examines how PBTs incorporate students' socio-cultural backgrounds when designing their CBSSIs classes; but doing so is important for fostering meaningful learning. Researchers have attempted to introduce SSIs to pre-service teachers (PSTs), such as Evagorou et al. (2014), focusing on how PSTs integrate content and pedagogical knowledge simultaneously; Espeja and Lagarón (2015) examined how PSTs conceptualise SSIs

using four categories: SSIs topics, controversy, uncertainty, and argument, and exploring PSTs' appreciation to teach SSIs; and Espeja and Couso (2020) emphasised that in preparing PSTs to teach SSIs, the lecturers should facilitate them to experience SSIs lessons themselves while also guiding them to design, implement and reflect on SSIs lessons. However, the efforts to introduce SSIs to PSTs in teacher training have not yet drawn on students' socio-cultural backgrounds despite the importance of providing meaningful and personally relevant science teaching. A deeper understanding of Indonesian lecturers and PBTs' perspectives is needed to understand how to develop a CBSSIs training programme for Indonesian PBTs to strengthen their skills in helping students navigate the complexity of science and culture. The research uses the Indonesian context because Indonesia is known for its diverse subcultures (Forshee, 2006). Also, there is still limited study of Indonesia's science education related to SSIs (Subiantoro et al., 2021). The research question is *What initial design principles can be used to develop a CBSSIs training programme for Indonesian PBTs*?

Methods

The study used a qualitative methodology. In answering the research question, a literature review and interviews were employed. Semi-structured online interviews were conducted with two Indonesian lecturers and three PBTs from one Indonesian public university. The selection criteria for the lecturers were those who had published a paper about SSIs, and the PBTs were based on their mixed abilities and coming from different parts of Indonesia. The consent forms were collected before the interviews. The interview protocols were adopted from the need analysis questions from McKenney and Reeves (2012) and questions from Subiantoro (2017) to explore the current landscape in teaching and learning SSIs and CBSSIs in the Indonesian context and ask lecturers and PBTs' needs and aspirations of the training programme. The interviews took around 1 hour each, mainly using the Indonesian language. However, some participants also spoke some English and Javanese (local language). After the five interviews were conducted, the interviews were transcribed for analysis. Then, the research participants were asked for approval to use the transcript. All of them agreed that the transcripts could be used in this study. The analysis was conducted in the original language spoken to maintain the nuance of the languages (Taber, 2018). The transcribed data were analysed using thematic analysis with the help of NVivo to extract initial design principles (IDPs) for a CBSSI-based training programme.

Results

The analysis reveals that the lecturers do not explicitly teach SSIs, as exemplified:

> "I basically do not structure it or do not, in the quote, "explicitly" like... "Let's prepare Biology education students to master SSI so that they can then implement the SSI learning model in schools". No. It's not explicitly structured the lesson like that" – Lecturer 2.

However, in the interview with the PBTs, PBT3 emphasised that they want to be explicitly taught SSIs. This preference can be incorporated as one of the IDPs, specifically focusing on *Understanding SSIs/CBSSIs,* as this is important in developing the training programme. It aligns with Anagün and Özden's (2010) statement that to be confident in teaching SSIs, understanding SSIs serves as a basis for introducing SSIs to PBTs, enabling them to teach CBSSIs.

In addition, Kolb's (1984) experiential learning theory highlights the importance of learning through experience. This theoretical perspective informed the training programme, equipping PBTs with authentic practice in designing and teaching CBSSIs. This idea also emerged from the interview, as the lecturers mentioned that PBTs should experience CBSSIs first-hand to help them understand the concept of SSIs/CBSSIs, suggesting that *Experiential learning* can be another IDP, where lecturers involve PBTs with direct experiences, as stated by Lecturer 1:

> "We, as lecturers, apply SSI-based education in the class. Then, we told PBTs that what is being applied is SSI-based education. Or we can do it the conventional way: PBTs are told or asked to look for it [SSI-based education] and then discuss it in class. But I think I'm more interested in the first one. By implementing it ourselves, the PBTs will experience it [SSI-based education] themselves." – Lecturer 1.

Furthermore, PBTs' understanding of SSIs/CBSSIs can be promoted through collaboration, such as a co-design and co-teaching scheme (Foulk et al., 2020; Huang & He, 2023), followed by a reflection session to enhance their understanding (Loughran, 2002). PBTs also explained that they need guidance in selecting and understanding appropriate issues for CBSSIs and analysing SSIs from diverse perspectives. PBTs also want their lecturers to support them in discussing and working collaboratively with peers in designing CBSSIs lesson plans, which leads to IDP *Collaboration and Reflection,* as PBT3 stated, "Maybe I only understand reproduction issues from my ethnicity. Maybe issues related to the circulatory or respiratory systems can be learned from other ethnicities." – PBT3.

The statement above from PBT3 also implied that the training should leverage PBTs' cultural background to introduce SSIs/CBSSIs. This also aligns with Lecturer 2's concern that teachers need to address SSIs in culturally different settings when designing CBSSIs lessons. The third space concept, arising from the literature review, will accommodate how science, culture, and society intersect in CBSSIs. In teaching SSIs/CBSSIs, PBTs need to address students' different cultural backgrounds (Tatham-Fashanu, 2023), facilitate the negotiation process between their everyday world and science class (Bhabha, 1990, 1994; Glasson et al., 2010), and navigate the tensions in SSI classrooms (Lee et al., 2020). These lead to the IDP of *Accommodating Third Space*.

Both lecturers and PBTs expressed that PBTs should be guided by lecturers in designing and implementing CBSSI lesson plans, which leads to IDP *Theory and Practice*, as stated by Lecturer 1, "I think it [the CBSSI lesson plans] would be more meaningful if implemented … Hopefully, everything will be implemented from the concept to the implementation. But if not, at least until the implementation." – Lecturer 1. It implies that, in addition to understanding the theory, PBTs need to practice what they have learned about teaching SSIs/CBSSIs to minimise the gap between theory and practice (Korthagen, 2010).

All five IDPs were extracted from the data analysis presented in Figure 1. These IDPs can be used to develop a CBSSIs training programme.

Figure 1. Initial Design Principles of CBSSIs Training Programme



Discussion and Conclusions

The study revealed lecturers' and PBTs' perspectives on the current teaching and learning of SSIs and CBSSIs and their needs and aspirations regarding developing the CBSSIs training programme. Enabling PBTs to understand SSIs and CBSSIs can be done through direct experiences as extracted to IDPs Understanding SSIs/CBSSIs and Experiential Learning. These findings align with research from Espeja and Couso (2020), who emphasised using the Experience-Design-Implement-Reflect pattern in preparing PSTs to teach SSIs. Espeja and Couso's (2020) work also aligns with the other IDPs: Collaboration and Reflection and Theory and Practice. PBTs collaborate with their peers in designing the CBSSIs lesson plan and reflect on their teaching skills. PBTs will also engage with theory and practice by implementing the CBSSIs lesson plan directly. This research found that Accommodating Third Space as an initial design principle is needed in developing the training. The third space theory provides a valuable framework to bridge students' background knowledge and science concepts in CBSSIs class. In the 'third space', students negotiate between their existing knowledge from everyday experiences and the novel concepts they encounter in science (Glasson et al., 2010). The third space can be used to explore and understand how science, culture, and society intersect to identify productive and culturally sensitive ways of negotiating science-society-culture in science education classrooms. In summary, five initial design principles (IDPs) were extracted in this study to develop the training programme, which are (a) Understanding SSIs/CBSSIs, (b) Experiential Learning, (c) Collaboration and Reflection, (d) Accommodating Third Space, and (e) Theory and Practice. This study provides a basis for science educators on what principles to use when introducing CBSSIs to pre-service teachers.

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Science Education And Communication: Innovative Methods To Promote Scientific Literacy

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The paper presents my Ph.D. research project, which aims to understand how to connect Science Communication (SC) and Science Education (SE) through edutainment, in order to develop Scientific Literacy (SL), which is necessary to cope with contemporary scientific and technological development (EC, 2015). To achieve this goal, we need innovative SE curricula that develop critical thinking (Akcay, 2018) and consider informal and non-formal educational contexts, such as SC on social media. The presented research is structured in two phases: an integrative review to identify the connecting elements of SC and SE through edutainment, and an educational research study aiming to exploit the educational benefits of SC in primary and middle schools. The results of the review allowed the creation of a teaching project based on active and cooperative learning methodologies, involving students as active users of SC and promoting SL. The research follows a phenomenological approach to explore students' and teachers' experiences and their meanings (Mortari, 2007) through different data collection methods. The final aim is to explore the benefits and challenges of SC in SE and to generate guidelines for STEM education to optimise and innovate the teaching experience.

Keywords: Science Education, Science Communication, Scientific Literacy

Introduction

This project addresses the need to enhance Scientific Literacy (SL) among 21st-century citizens (Serpa et al., 2021) in response to rapid scientific and technological development (EC, 2015). SL integrates knowledge and critical thinking (Ah-Namand & Osman, 2018), facilitates informed decision-making and responsible citizenship (EC, 2015) and develops through both formal setting with Science Education (SE) and non-formal setting with Science Communication (SC) (EC, 2020a). To be effective, SE should adhere to a multidisciplinary, reflective approach that fosters both disciplinary expertise and critical thinking (Akcay, 2018). As regards the SC, it raises awareness of STEM issues, fosters public trust in science (EREA, 2022), and conveys messages through accessible language, interaction and engagement, creating edutainment, an entertaining form of education (EC, 2020b). Moreover, digital technologies (which often play an essential role in conveying SC) facilitate interactive relationships between disseminators and audiences, promoting critical perspectives and responsible behaviour (López-Goñi & Sánchez-Angulo, 2018).

It is clear that SE and SC have areas of fruitful interaction, but despite their shared aims, their connection remains absent in educational practice (Everhart, 2009), due to a lack of research-based guidelines (Lewenstein & Baram-Tsabari, 2022). However, science communicators on social media contribute to public education, revealing a latent synergy between SE and SC. This dynamic became particularly evident during the COVID-19 pandemic, which underscored the need for education to address the infodemic through SC (WHO, 2020). As this occurs without explicit pedagogical frameworks, it can lead to an underestimation of the educational and formative potential of this tool, or its ineffective use.

This illustrates the urgency of innovation in STEM education, which requires a theoretical and practical bridge between SE and SC on social media through edutainment. This research aims to highlight its benefits and risks, offering insights, instruments and guidelines for STEM education,

shaped for teachers and shareable within different contexts, to innovate the teaching experience (Jorde & Dillon, 2012; Akkerman et al., 2021).

Research Design And Methods

Starting from the element that emerged from the initial literature review, the research is based on two research questions:

What are the most effective prompts offered by science communicators on social media, connected with edutainment, that it is possible to use to connect SC e SE positively?

How can be designed and realized teaching and learning project in the STEM area for different school levels (primary and middle school) which exploit the potential of SC in terms of engagement and use it as a stimulus to the development of SL?

The research design is structured into two phases to answer the two research questions. The first is an integrative review, which aims to identify the relevant theory and effective practices. The second is an educational research study, designed according to the results of the literature review, and implemented in primary and middle schools to foster SL development and assess its effectiveness.

Integrative Review

The first phase aimed to investigate, through a literature analysis conducted by an integrative review method, the relationships and implementation lines between SC on social media and SE through edutainment. The integrative review encourages complex phenomena investigation by connecting theoretical and empirical literature and focusing on the context, processes and subjective elements of the phenomenon, revealing different perspectives (Whittemore & Knafl, 2005). The databases consulted were JStore, Eric, Scopus, while the search strings contained the terms: “science education”, “science communication”, “edutainment” and “social media”. The search period covered twenty years, from January 2004 (the year Facebook appeared) to January 2024. Thirty-two papers were selected, and their analysis offered a theoretical background and practical-operational suggestions useful for the subsequent teaching project. They present teaching activities that link SC and SE through edutainment, employing different social media to propose a scientific mindset and content (Makarius, 2017) and facilitating learning (Swensen et al., 2014). Such tools are relevant for young people (Danielsson et al., 2023), as they share information and interests creating discussing networks (Bigelow & Kaminski, 2016). In the education context, they can promote peer-to-peer knowledge (Karahan & Roehrig, 2015), debate lesson-related content, and foster a process of knowledge co-construction (Dubovi & Tabak, 2020). This facilitates students' involvement both inside and outside the classroom, increases collaboration and creates a sense of community, leading to enthusiasm, motivation and engagement (Caratozzolo et al., 2022). Furthermore, they encourage content acquisition, creative thinking, problem-solving, and a reflective and searching perspective on scientific content (Bigelow & Kaminski, 2016). Such skills are needed as people increasingly search for information, including scientific information, online (Karahan & Roehrig, 2015). Individuals follow scientific content online for personal and educational interests (Rosenthal, 2018), but there is a risk that they assimilate information without critical thinking (Szu et al., 2017). Indeed, social media are nowadays, together with the school, among the educational contexts in which the scientific learning process takes place (Reid & Norris, 2016). In order to maximize the transformative potential presents in the relationship between SE and SC, it is necessary to design and promote innovative teaching methods that consciously integrate them. They should be linked with a specific effort aimed at educating young people to use all the tools at their disposal as a

stimulus to inform themselves and stimulate their curiosity, such as social media, which today represent a priority vehicle for the SC.

Teaching Project

The integrative review provided essential insights for the design of a teaching project that integrates SE and SC on social media through an edutainment approach. These findings served as the basis for the creation of two different teaching programs, which were adapted to the specific educational stages, one for fifth-grade primary and one for third-grade middle school students, and consisting of four/five sessions, lasting one to two hours each. The learning objective is to foster SL by promoting the development of scientific knowledge, as well as critical thinking and digital and information skills. To achieve this, the project employs Active Learning and Cooperative Learning methodologies. It emphasizes interactive activities that encourage students in active participation and engage them in both practice and reflective analysis moments. The project is structured into four phases, each of which is presented through practical activities related to the participants' personal experiences to facilitate understanding of the topics:

1. *Critical analysis of SC content*: students identify key indicators of effective SC (e.g. clarity, accuracy, engagement, etc.) reflecting alone and in pairs. This phase is useful for assessing the content reliability.
2. *Research on a scientific content*: after viewing a SC content video, in small groups, students define their topic and search sources and online information about it. During this phase, they assess the reliability and quality of the sources.
3. *Production of SC content*: students work in small groups to design communication plans and create videos using digital tools. The activities enhance and consolidate their learning.
4. *Sharing and discussing:* students present their content both in class and on dedicated social media platforms (created with appropriate ethical considerations of their use in an educational context), trying to be science communicators.

These steps are aimed at developing SC skills, from the search for information to the effective presentation of content, promoting teamwork and critical evaluation of sources and social media content. The goal is to shift students from passive to active consumers, enhancing their awareness of SC mechanisms through its implementation and fostering their role as student researchers and communicators, integrating scientific knowledge within a broader framework of knowledge and experience. Moreover, teaching programs were refined in collaboration with classroom teachers to ensure effective integration into existing curricula, addressing both content and pedagogical needs in different contexts. Meanwhile, an educational research study was conducted to assess the program's effectiveness, adopting a phenomenological approach to examine students' experiences and the meanings they attributed to them (Mortari, 2007).

Data Collection

The project was implemented in six schools located in different areas: the city centre, the suburbs and outside the town. Throughout the implementation phase (before, during and after), data were collected using various methods to capture different dimensions of the project.

Firstly, field notes and eye-guides completed during participant observation, together with pre-intervention teacher interviews, were used to understand the contexts and their specific needs, so that the educational project could be adapted accordingly. Pre- and post-intervention teacher interviews also provided insights into teachers' perspectives on the project, helping to identify its effectiveness and weaknesses from the viewpoint of key participants. Alongside the teachers' thoughts, students' opinions were gathered through self-assessment activities and audio

recordings of classroom discussions. Further data were collected to evaluate the project's two key objectives. The first aim focused on the development of critical abilities in evaluating sources and videos, and was examined through pre- and post-tasks, along with analysis, reflections and discussions on two videos, classroom audio recordings of dialogues and students' online searches. The second goal concerned the ability to produce a video, and was investigated using data on communication designs, student-created videos, and audio-recorded discussions.

Data Analysis

The data analysis is ongoing and follows a phenomenological approach, which requires conducting research in the field and observing phenomena as they occur, with the aim of understanding the lived experiences of participants (Mortari, 2007). The data are analysed using inductive content analysis (Elo & Kyngäs, 2008) and crystallisation technique (Ellingson, 2009).

Inductive content analysis is useful as often used to manage large volumes of textual data from diverse sources (Prasad, 2008), as in this research. It requires to transform the data into content-related labels and categories, creating a coding system (Elo & Kyngäs, 2008). Specifically, labels emerge directly from the text data becoming a coherent description of the studied phenomena (Elo & Kyngäs, 2008; White & Marsh, 2006). Different coding systems can be compared, allowing to create logical inferences between them. Moreover, the crystallisation technique facilitates the integration of these diverse forms of analysis into a coherent narrative. The aim is to gain a deep understanding of the phenomena by examining them from various perspectives using different types of data in order to reveal their nuances (Ellingson, 2009).

All the collected data cannot be analysed using the same method. Particularly, the videos produced by children require the development of a specific framework and an evaluation grid. This framework was developed through a literature review conducted using content analysis, which identified key elements to consider when producing SC videos for social media. Based on these elements, a supporting instructional tool was developed and proposed to the children, and an evaluation grid was derived from it and used to analyse the video data.

First Results

As seen, data collected allow to investigate different dimensions of the project, the results will describe these elements. Specifically, the educational research study investigates SC's educational potential by observing and analysing the setting, people interactions, their experiences, thoughts and learning objectives, allowing to investigate the effectiveness and areas for improvement of the project. Firstly, a preliminary context analysis was conducted using participant observation, eye guides and semi-structured interviews with teachers. Based on the data collected, the teaching project was refined according to the characteristics of each classroom, ensuring both research relevance and pedagogical applicability. For instance, the online information search activity was implemented in different ways based on dialogue with teachers regarding students' abilities. In particular, in some primary school classes, students could not find information online alone due to lack of digital skills, which is understandable given their age. For this reason, we decided to provide them with pre-selected online materials, including the necessary information for a reflection, such as source links, text and pictures. In these cases, the aim of the activity was not to find information online on their own, but rather to encourage critical reflection on the provided materials with the guidance of adults. Therefore, the program was designed and implemented in collaboration with teachers, recognising and respecting their professional expertise and class knowledge.

The remaining data are currently under analysis, with a particular focus on the perspectives of the main actors (students and teachers), as well as the two central themes. The first concerns the

development of critical thinking skills in the evaluation of online sources and videos. The second relates to students' ability to produce SC videos for social media, an activity that enables students to internalise the effective elements of such videos. Through this process, they become more aware of, and more critical of, the potential risks and benefits of online SC videos in their daily lives. Both abilities are necessary for developing students' SL, as they encourage critical thinking about scientific content and the development of an informed and conscious awareness of them in relation to everyday situations.

Conclusion

In conclusion, the project included an integrative review phase to identify the theoretical foundations and practical-operational insights present in the literature on the integration of SE and SC through edutainment on social media. The results of this review guided the design of an educational project aimed at promoting this integration in order to effectively fostering SE through an interactive and engaging approach that encourages students' critical thinking and SL, transforming them from passive to active users of SC. This process is part of an educational research study that examines the effectiveness of the teaching program by identifying both its strengths and limitations. To achieve this, various types of data were collected throughout the project's implementation, such as participants' perspectives and data on educational goals, that are currently being analysed.

Finally, the project aims to develop guidelines for STEM education innovation that align with technological advancements while bridging formal and informal learning environments and promoting informed decision-making and responsible citizenship among students. The research wants to contribute to the development of more effective and engaging STEM education strategies addressing the current social context.

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Understanding AI In Secondary School Education: How Technical Knowledge Affects Students' Technology-Critical Understanding

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Machine learning is widely used in society today. It is therefore crucial that children and young people develop insights into how machine learning works, as well as technology-critical skills to discuss and impact how AI and machine learning are used today. In this study, we present a first analysis to understand the interplay between technical and technology-critical skills, focusing on the reflections of lower secondary school students from interviews. Preliminary findings indicate that while some students developed an understanding of machine learning mechanisms, others struggled to relate machine learning to the real world. We discuss which relevant technical aspects of machine learning are needed for students to become able to develop technology-critical skills. Future research should explore how focusing on technical aspects in a deeper and more specific way affects students' technology-critical understanding.

Keywords: AI Literacy, Critical Thinking, Secondary Education

Introduction

In educational research there is an awareness of the importance of preparing students for a society that extensively uses AI. Curricula about AI and machine learning have been developed (Chiu, et al., 2022; Touretzky et al., 2023), and studies on societal impacts of AI have been conducted in relation to AI literacy (Lee & Kwon., 2024; Demir & Güraksın., 2022; Zambach, 2025). Those works are of importance for future generations' understanding of this domain in regard to taking a critical stance on the use and development of AI in society (Elicer et al., forthcoming).

The increased use and acknowledgement of machine learning and AI in society calls for more development and integration of curricula about AI and how it affects everyday life as well as teaching and learning (Yue et al., 2022; Smith et al., 2023). In that context, the purpose of this study is to explore secondary school students' understanding of machine learning. We present interview data as well as a work in progress analysis that maps the participating students' ability to critically understand the use and development of machine learning in society, based on their experiences with developing and discussing a machine learning model.

In this work-in-progress study we address the question:

How do lower secondary school students understand machine learning, and how do they reflect on technology-critical aspects of it based on their experiences in the classroom?

We investigate this using design methods and data consisting of six focus group interviews with students from 7th, 8th and 9th grade in a Danish school.

Case

This analysis is part of a research project based on developing a teaching sequence designed for lower secondary school in the context of biology as a school subject and using a scenario-didactic teaching approach (Fougt et al., 2022). The purpose of the research project is to examine students' understanding of machine learning models in the world, and to be able to critically evaluate the use of and responsibly develop such models in a STEM-context. In this context, technology-critical aspects refer to students' ability to critically reflect on topics such as ethical dilemmas and data usage in relation to society.

The course consists of a scenario where students act as employees in a fictional company that develops apps for health-tracking. In its current form, it has a duration of nine lectures of 45 minutes. By using Machine Learning for Kids (https://machinelearningforkids.co.uk/) to classify different images of food into different health related categories, the purpose is for students to learn the fundamental principles of machine learning models. After playing out different scenarios where the company enters a partnership with a fictional recruitment company, the students are to critically reflect on responsible usage of data and the influence on data-based algorithms in society. Afterwards the students discuss societal and ethical issues regarding the scenario. See an overview of the teaching lessons in the table below (Caeli et al., 2025).

Table 1. Overview of the teaching lessons.

Part 1: Preparation/Onboarding (3 x 45 minutes lessons)
Lesson 1: ***Welcome***
Brief, phones, teams and welcome folder.
Lessons 2 and 3: ***Onboarding***
The students work through an onboarding process as part of the newly started development department (an introduction and initial course in the program Machine Learning for Kids). The onboarding process is available as a step-by-step guide on a fictional intranet.

Part 2: Development (6 x 45 minutes lessons)
Lessons 4 and 5: ***Developing the food app***
Video 1: The CEO of the fictional company explains the task. The students discuss how to categorize food into healthy and unhealthy and assign a score. Students are then told to categorize their images into healthy, medium and unhealthy. They work on their model in Machine Learning for Kids, i.e. categorize the images and train the model.
Lessons 6, 7 and 8: ***Developing the health app***
Video 2: The CEO of the company announces the partnership with a fictional recruitment company. Students discuss and make notes on what data to collect about health, create a scoring system, test their solutions, create wireframes of the app, and see a dashboard for the recruitment company.
Lesson 9: ***Discussing responsible development***
Department meeting: Discussion of the categorization, reaction to the deception of users (discussion on ethics and responsible development). Half of the teams must argue *for* and half must argue *against* profiling and selling data. Department meeting: The groups present pros and cons. They discuss whether their company should continue down this path and consider ethical principles for responsible development.

A pilot study was conducted in the spring of 2023 (see Caeli et al. 2024), the first full design cycle was conducted in April 2024, and the last iteration was conducted in November/December 2024.

Methods And Data

The following presents the methodological basis for interviews and the collected data.

Method

The research project was developed as a design study in collaboration between researchers and teachers. Data was collected through face-to-face qualitative focus group interviews, using semi-structured interview guides on specific themes. Open-ended questions elicited students' opinions, thoughts, and experiences to enable further course development and iterations (Creswell & Creswell, 2018).

The focus groups were interviewed prior to the development of the teaching sequence (August 2023) and follow-up interviews were conducted after the teaching sequence (December 2024, different students). The purpose of the interviews was to gain insight into the participating students' technical and technology-critical understanding before and after being taught a teaching sequence in machine learning in order to develop more relevant and appropriate teaching.

The preliminary interviews covered three themes: 1) Machine learning understanding, 2) Critical stance on machine learning and 3) Interaction between biology and machine learning. Follow-up interviews included questions on scenario didactics and teaching.

To answer the research question, we focused on: 1) Understanding machine learning and 2) Critical stance on machine learning in a biology context. In addition, we had a specific view on the relationship between technical skills and technology-critical skills in the classroom, based on experiences from our pilot. Additionally, we chose to use the term AI instead of machine learning because we expected students to be more familiar with this term. All interviews were coded in Nvivo.

Data

The data consists of interviews with students from lower secondary school as illustrated in the table below.

Name	**Period**	**Type**	**No of participants**	**Level**
Pre1, Pre2	Preliminary	Focus group interview	2 groups of 4 each	9th grade
FO1, FO2, FO3, FO4	Follow-up	Focus group interview	4 groups of 4 each	2 classes from 7th grade and 2 from 8th grade

Findings

In the following we present our findings based on the two areas mentioned above.

Understanding Machine Learning

In the preliminary interviews, some of the participating students expressed that they lack, and would like to have, an understanding of how AI works, how it is used, and exactly what data is being collected by, for instance, social media. It also appeared that most of the participating students did not have any immediate thoughts about how machine learning works. However, one

student (Pre2), stated that AI can be used to create images, indicating an awareness of AI's capabilities.

From the interviews, some of the participating students seemed to have a broad understanding of the fact that the computer/machine is not intelligent in itself. A student expressed that it is humans who make the machine intelligent (FO1). Another student stated that it is not the machine that is intelligent, but that it is programmed and coded (FO3). In another interview, the students agreed that the machine is not intelligent like a human, partly because it does not know who the user of it is (FO4). From another interview a student expressed that it is the data that the computer uses that is intelligent, not the computer in itself (Pre2).

In one interview, a student presented an interesting opinion when answering yes to ChatGPT being intelligent because it is an artificial intelligence, putting emphasis on the word intelligence. Another student then emphasized that the intelligence is artificial and thus has a different understanding of why it is not intelligent (FO4).

In the follow-up interviews, we observed an overall understanding that the machine can learn (FO1-FO4), but, interestingly, not an overall understanding of how it works or what it actually is, which was one of the learning objectives in the project.

Critical Stance On Machine Learning

All students in Pre2 are aware that apps like TikTok, Netflix, and Instagram use data about them to target content. They seem to have an awareness and understanding that machine learning is used in many areas, although they seem to have a general understanding of AI.

In general, the students participating in the follow-up interviews are reflective about how organizations monitor data. One student reflected that the benefit of targeting ads lies with those who make money from them, but the student does not think it is okay that they know so much about the user (FO1). This attitude is echoed by another student who added that it is scary and weird that someone can know so much about you but also expressed that it is smart because it personalizes your experience (FO1). Another student agreed and is happy not to be shown useless videos (FO3) instead of (useful) user targeted content, and another said that machine learning is smart because you do not have to watch content you do not like (FO4).

Thus, a variation of what appears to be informed use seems to be present among the participating students, who take positions both for and against user targeted content (recommender systems) in, for example, social media. However, in another interview (FO3), the students expressed that they would like to know more about what AI does and how data is used by the company. In contrast to this, a student from another interview expressed that it is not necessary to learn about AI in their opinion (FO4).

Discussion

One observation was that while the students were taught how machine learning works, what data is, and critical aspects of data use, some students expressed they did not know what AI does and how data is used. As our teaching material focuses on the machine learning mechanism of image classification as part of a “health-app”, perhaps the machine learning method related to the critical discussion about the use of data should be supplemented with deeper technical understanding, in this case of recommender systems. Recommender systems are another type of machine learning than classification methods, and they create the basis of the recommendations of social media. Likewise, the discussion was also affected by opinions on ChatGPT which is based on generative AI - yet another type of machine learning.

A practical implication of this finding is that when teaching machine learning, it is important to distinguish between these different types of machine learning methods and focus on the ones important for the project. Additionally, one could discuss the taxonomy of these in class for students to have a better chance of understanding different technical aspects of machine learning - and thus possibly also technology-critical aspects on a higher level.

Interestingly, we saw a similar pattern in a pilot study (Caeli et al., 2024), in which we had included block code programming for introducing deeper computational thinking (MIT App Inventor, https://appinventor.mit.edu/). This seemed to be time-consuming and distracting for students' technical understanding of machine learning, so we removed the block programming content in subsequent iterations.

Future research could consider exploring how deeper and more specific focus on technical aspects affects students' technology-critical understanding, i.e. the balance between the two aspects.

There are inherent limitations to this study, which is a work-in-progress study and thus focuses on a relatively narrow scope. Additionally, the study's reliance on a specific educational context in one school may not capture the full diversity of student experiences and understandings.

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Part 9 / Strand 9

Science Education For Sustainability, Agency And Futures Literacy

Co-editors: *Olivia Levrini & Laura Colucci-Gray*

Part 9 / Strand 9 Science Education For Sustainability, Agency And Futures Literacy

Theories, methods, and practices of science education for sustainability, agency, and futures literacy. Includes future-oriented proposals for framing science education research agenda into contemporary debates on agency, sustainable development and sustainability education as well as analysis, discussion and reflection about both contemporary and foundational competence frameworks, reports and agendas at the European and international level.

Sub-themes:

1) Theories, methods, and practices of science education for sustainability
2) Theories, methods, and practices to Foster Agency and Empowerment
3) Futures Literacy and Future Thinking in Science Education
4) Policy and Practice in Science Education for Sustainability

Contents

Strand 9: Science Education for Sustainability, Agency and Futures Literacy 718
Trade-Offs In ESD Related To Using Wind Energy – A Study Conception 720
Exploring Students' Conceptions Of Critical Raw Materials And Their Availability 726
Sustainable Competencies In Education: Building Curricula And Advancing Teacher Training Together 734
'How Sustainable Is ...?' A Teaching Approach In The Field Of Education For Sustainable Development 742
How To Teach In Times Of Biodiversity Loss: Pedagogical Approaches To Transform Our Relationship With Nature 751
Cross-Cultural Analysis Of Stem Human Resources Community Influences On Gender: Focus On Higher Education Students In Japan, America, And Malawi 760
In Science We Trust? Examining Institutional Trust, Information Sources, and Climate Literacy Among Future Teachers 765
Potentials And Challenges Of Serious Games In Environmental And Sustainability Education 775
Designing Future Cities: Using Futures Literacy To Promote Youth Agency 782
Implementation Process And Outcomes Of School Climate Assemblies: Exploring The Views And Perceptions Of Secondary School Students 787
Placemaking Reimagined: Examining The Role Of Imagination In Critical Place-Based Learning 793
A Regression Analysis Of Environmental Attitudes And Interest In Environmental Topics ... 799
Exploring Competences Of In-Service Teachers In Implementing Education For Sustainable Development 808
Assessing Students' Sense Of Responsibility In Chemistry Education: Development And Validation Of An STSE-Based Instrument 821
From Instrumental To Communicative Rationality: Reimagining Science Education For Sustainability In Socio-Political Conflicts 829
Greek Chemistry Teachers' Perspectives On The Integration Of Green And Sustainable Chemistry Practical Activities In Secondary Education 836
Science Teachers' Democratic Assignment: A New Vision Of Scientific Literacy And Civic Engagement For A Futuristic, Fair And Sustainable Europe 841
Empowering Children As Agents Of Climate Action: A Case Study Of A Teacher's Enactment Of Socio-Scientific Inquiry-Based Learning In A Kindergarten 848
Facing Scenarios Of Ontological And Epistemic Uncertainty In Science Teaching: Perspectives On Agency In The Literature In The Field 855
Expanding Perspectives on Agency within Climate Change Education Debate 863

ESERA 2025 Copenhagen

Strand 9: Science Education for Sustainability, Agency and Futures Literacy

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Strand 9 brings together research concerned with the role of science education in addressing sustainability challenges, socio-scientific complexity, civic participation and futures-oriented science education. The strand focuses on how learners, teachers and educational communities can engage with environmental, technological and social issues that are uncertain, contested and ethically charged. Across the contributions, science education is not framed simply as the transmission of scientific knowledge, but as a space for developing responsibility, agency, critical reflection, communicative rationality, future literacy and democratic participation.

The papers included in this section cover a wide range of sustainability-related themes. Scientific literacy continues to be a strong theme particularly in relation to political and structural issues associated with the energy transitions. Several contributions go in depth about the significance and necessity of bringing together disciplines across the natural sciences to address social and environmental challenges, including biodiversity loss, green infrastructures, ecosystem services, wind energy, critical raw materials, bio-based plastics, vegan diets and green and sustainable chemistry. These papers explore how science education can make complex environmental issues meaningful for students and teachers by connecting scientific concepts with ethical, emotional, political and everyday dimensions of sustainability. In this sense, the strand strongly reflects the conference theme of sustainability, showing how environmental issues are increasingly approached through interdisciplinary, participatory and action-oriented pedagogies.

A second important group of contributions focuses on Education for Sustainable Development, Global Citizenship Education. These papers examine teachers' competences, willingness and pedagogical preparation for integrating ESD into school and university contexts, including technical and higher education. Ongoing attention is given to the importance of teacher preparation learning through professional development courses, exploratory seminars, interdisciplinary teaching and design-based approaches which supports students in assessing sustainability controversies from environmental, economic and social perspectives. Together, these contributions highlight that sustainability-oriented science education requires not only new topics, but also new forms of curriculum design, teacher learning and institutional support.

A third set of papers foregrounds responsibility, agency and civic engagement. Contributions examine a wide range of assessment tools for measuring students' sense of responsibility in chemistry-related STSE contexts, which emphasise wider civic competencies with practical applications in climate assemblies, opportunities for youth participation, placemaking, and collective and political agency in the Anthropocene. These studies point to a shared concern: students need opportunities to participate in decision-making, imagine alternative futures, engage with uncertainty and act in relation to complex global challenges such as climate change, biodiversity loss and social inequalities. Approaches such as serious games, imagining futures are offerings which are multi-modal and participatory. These contributions also resonate with the conference theme of digital advances suggesting that digital and game-based environments can support imagination, systems thinking, collaboration and engagement with complex sustainability issues when they are embedded in critical and pedagogically meaningful designs.

Positioned within the wider field of science education research, Strand 9 contributes to ongoing debates on scientific literacy, STSE education, socio-scientific inquiry, ESD, climate change education, and democratic approaches to science education. The contributions collectively challenge narrow technocratic views of science education and call for pedagogies that are more relational, critical, participatory and future-oriented. They portray science education as a key site for preparing learners and educators to understand complexity, to deliberate about values, to imagine desirable futures and participate responsibly in the transformation of society towards more just and sustainable worlds.

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Trade-Offs In ESD Related To Using Wind Energy – A Study Conception

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The use of wind energy is highlighted in the interests of sustainability. At the same time, wind turbines harm the environment due to their demand for raw materials and their purification processes. A trade-off is required. For education for sustainable development (ESD), this expresses the need to promote evaluation skills in addition to the transfer of knowledge about raw materials. Research is already being carried out on the contents of raw materials, evaluation skills, and dealing with trade-offs within ESD. This project aims to expand the discussion of raw materials in the context of wind turbines while incorporating new evaluation perspectives, including emotional interaction. This is considered particularly relevant in the emotionalised context of ESD trade-offs. Therefore, an intervention study monitors the interaction of school students with different presentations of the trade-offs related to wind turbines. The article shows the structure of the project, the methodological approach as well as initial findings from the first study.

Keywords: Education for Sustainable Development, Raw Materials, Emotion

Introduction

Global warming increasingly poses a threat to the environment. To reduce the impact of energy supply on the climate, efforts are being made to expand renewable energies such as wind energy, as set out in SDG 7.2. No greenhouse gases are released when wind energy is converted into electrical energy. Nevertheless, the energy supply with wind energy is not ‘neutral’ in terms of climate and environment. Raw materials such as iron, copper, rare earth elements, aluminium and carbon fibre are required for the construction of wind turbines (Rueda-Bayona et al., 2022).

With its demand for raw materials and the associated purification processes, the technology declared sustainable in SDG 7.2 counteracts the efforts of SDG 15 to a certain extent; making a trade-off necessary. Such trade-offs over raw materials are represented more transparent in the media, most recently concerning lithium mining (e.g. Santos, 2024). This can be overwhelming for school students. ESD aims to support students develop the skills they need to help shape sustainable development despite trade-offs. The ability to allow ambiguity and to learn balancing different goals are central to these skills (UNESCO, 2020). Therefore, when dealing with trade-offs in ESD, it is necessary to analyse the content of raw materials but also train evaluation skills and create a framework that allows for ambiguity. In doing so, the emotional impact of the content needs to be considered in addition to the content itself.

In the following, the context of wind turbines presents the content level. While fossil-fuelled energy plants place a heavy burden on the environment during the operational phase, wind energy has almost no impact on these factors during operation. But what about the phases before and after operation? Life cycle assessments include these steps in their endpoint categories of ecosystem, human health, and resource depletion (Rueda-Bayona et al., 2022). They show that wind energy plants have the greatest impact on the environment in their production including the mining, beneficiation and purification of raw materials (Xu et al., 2018). These processes require energy and chemicals and release emissions into soil, water, and air. This can be exemplified by the purification of the rare earth element neodymium. Neodymium is used in permanent magnets in the generators of some wind turbine types. Usually, concentrated sulphuric acid is used for leaching of neodymium-containing ores, e.g. fluorocarbonates. This produces harmful by-

products such as hydrogen fluoride. In addition, radioactive thorium is released, and acidic wastewater remains due to incomplete reactions (Schreiber et al., 2021).

Even though life cycle assessments identify different environmental impacts of wind turbines, the primarily impact is the abiotic resource depletion potential of chemical elements (Atilgan & Azapagic, 2016). The impacts can be varied depending on decisions in three areas: the energy plant itself (Atilgan & Azapagic, 2016), the raw materials used (Schreiber et al., 2019), and the processing of the raw materials (Li et al., 2019).

Although the trade-off is dealt with, scientifically, in life cycle assessments, it is hardly ever recognised in society and schools. So far, school students have made an undifferentiated distinction between renewable and non-renewable energy use with the descriptions clean and dirty (Hüfner, 2020). A differentiated evaluation allowing ambiguity must be aimed, for example with the process-oriented framework PAAWD^{R} (Langlet et al., 2022). It allows to focus on ambiguity, criteria determination, and balancing more closely, which are of particular interest in these complex trade-offs in ESD. PAAWD^{R} divides the process into the steps of perceiving, analysing, arguing, weighting, deciding, and reflecting (Langlet et al., 2022).

Regarding the perception, it requires an openness to engage with the trade-off and to allow nuances between the clean-dirty distinction. In ESD contexts, the emotional preload and reaction should not be overlooked, especially due to the nature of the challenge in trade-offs. Studies show that learning in the context of climate change can evoke worries, hopelessness, and helplessness. Half of young people are very worried about climate change (Hickman et al., 2021) and disillusioned about a sustainable future (Grund & Brock, 2019). The sometimes resulting helplessness (Kuthe et al., 2020) runs counter to the aim of ESD to promote the ability to shape the future.

In addition to their impact on society, emotions such as fear and hopelessness can be harmful to the learning success. In achievement emotions, positive activating emotions such as joy were found out to be the most promising, and negative deactivating emotions such as hopelessness the least promising (Pekrun et al., 2007). The feeling of hope can counteract paralysing fear or hopelessness (Kleres & Wettergren, 2017). Grund and Brock (2019) therefore encourage emotionally sensitive ESD with the promotion of constructive hope. This in mind, solution-oriented approaches are developed along the sustainability strategies of sufficiency, efficiency, and consistency (e.g. Applis et al., 2022). In this research project, aspects of these solution-oriented approaches will serve as inspiration for the design of the intervention and learning content.

Aim And Research Questions

The aim of the whole project is to design a learning unit for chemistry. Using the example of the raw material demand for wind turbines, the unit should introduce school students to an emotionally charged ESD trade-off in a sensitive manner and support them in making differentiated evaluations.

To this end, two key questions with sub questions will be investigated and categorised according to the PAAWD^{R} model. The first question focusses on perception. The second question covers weighting, deciding, and reflecting.

1. How do school students perceive different facets of the trade-offs on wind turbines?
   1.1 Which area would they like to deepen?
   1.2 Which emotions occur while being confronted by the trade-offs?

2 What information is relevant for school students in their decision-making process of the trade-offs regarding wind turbines?
  2.1 Which criteria are important to them?
  2.2 How does their evaluation change?
  2.3 Why does their evaluation (not) change?

Method

Within this project, the research questions are investigated through two studies using a mixed-methods design. The study presented here focuses quantitively on students' perception of the trade-offs (RQ1, $N = 129$). It was conducted in 2025 with 10th and 11th grade students. The second research question (RQ2) will be addressed qualitatively in a separate forthcoming study.

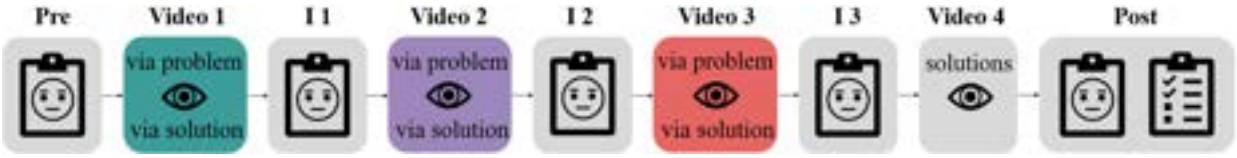
The trade-offs addressed in the study cover the three areas mentioned: energy plants (contrasting wind energy and natural gas plants), raw materials (contrasting the use of a higher amount of copper to rare earth elements in the generator of an energy plant), processing (contrasting pyrometallurgical and hydrometallurgical methods). The trade-off interventions are presented as videos with a duration of two to three minutes. Moreover, the subject of solution perspectives is addressed, using examples from the sustainability strategies sufficiency, efficiency and consistency (see table 1).

Table 1. Content of the intervention.

	Energy plant	**Raw materials**	**Processing**
Problem-oriented trade-off	Wind energy vs. natural gas	Copper vs. rare earth elements	Pyrometallurgical vs. hydrometallurgical
Added solution approach	Sufficiency	Efficiency	Consistency

The study was conducted with an online questionnaire (duration: 30 min) including a pre-test, video interventions on the trade-offs, a post test, and a video on solution approaches. In addition, there were brief intermediate measurements after each video (see Figure 1). The trade-off interventions were carried out in two groups. Group A was introduced to the trade-off directly via the problem. Group B was introduced to the trade-off via a solution approach that reduces the extent of the trade-off beforehand.

Figure 1. Structure of intervention (I: intermediate measurement, face: emotion measurement, eye: video intervention, list: selection of topics).



The intermediate measurements assess the emotions dimensionally using the Self-Assessment Manikin (Bradley & Lang, 1994). The emotions were further assessed categorically pre and post using a 5-point Likert-scale (adapted from Duffy et al., 2020). Moreover, students' attitudes towards wind turbines were assessed, and in the post-test, they selected the trade-off topic and solution approach they would like to explore further as well as whether they would like to study one of the two selected topics in greater depth than the other.

Data with more than 30% missing values or unusually fast processing times (RSI > 2; < 25 s on intervention pages) were excluded, leaving $n = 99$. Analyses were conducted in *IBM SPSS*

Statistics 29.0.0.0. The topic selection is described via frequency distributions (RQ1.1). Since the emotion variables are not normally distributed (Shapiro-Wilk-test: $p < 0.001$), Wilcoxon test will be applied for the categorical emotions and Friedman test for the dimensional emotion assessment (RQ1.2).

Initial Results And Discussion

The analysis for RQ1 is still ongoing. However, the initial results of the analysis of the frequency distribution of the topic selection (RQ1.2) have already been obtained. These results show a clear tendency within the trade-off-topics to deepen the trade-off concerning energy plants, as well as a desire for solution approaches to be discussed.

The majority of students (62,6%) want to expand the trade-off between wind energy vs. natural gas use. The trade-offs in the areas of raw materials and processing are similarly chosen (see figure 2).

Figure 2. Initial results of the selection of a problem-oriented trade-off topic.

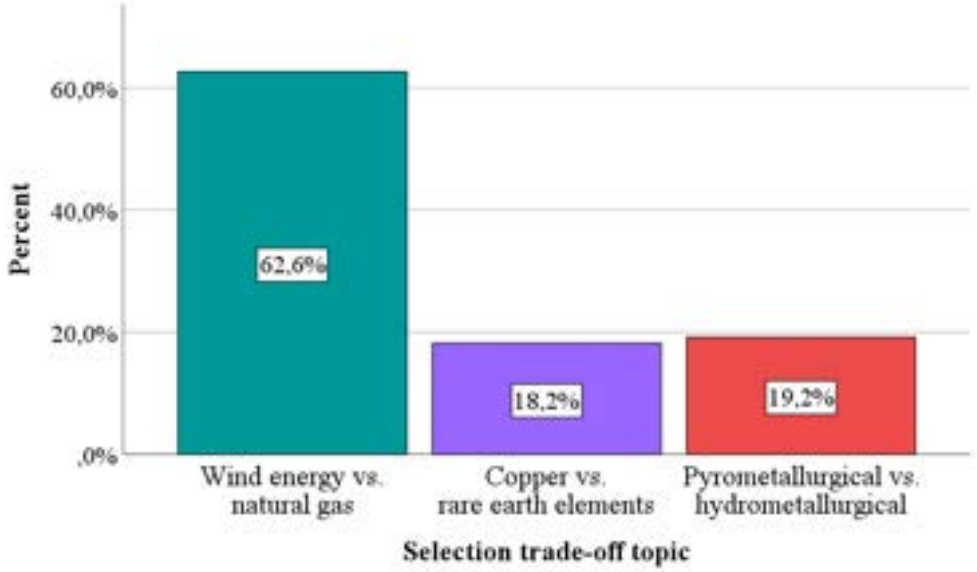
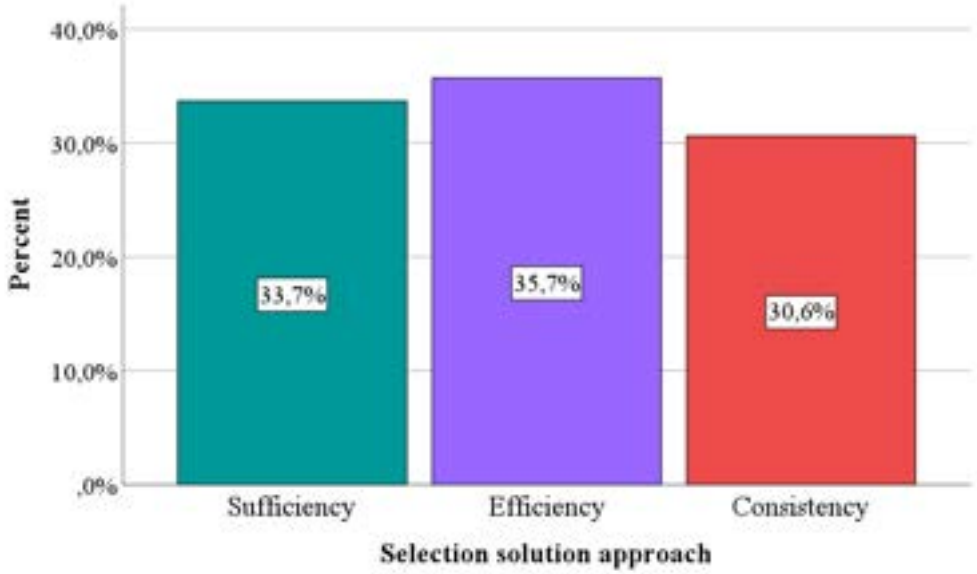


Figure 3. Initial results of the selection of a solution approach



The solution choice is more evenly balanced with a slight preference for the efficient use of raw materials (35,7%, see Figure 3). Comparing the selected trade-off topic and solution approach, only nearly a fourth of the students want to focus on their problem-oriented choice (24,2%) in

further lessons. More students want to concentrate on the solution approach (35,4%) or equally both (39,4%).

Based on the results of life cycle assessments and the objectives of ESD, this article emphasises the importance of addressing trade-offs related to the use of raw materials. It presents potential topics in three areas as well as school students' preferences within these topics. Both trade-off topics and corresponding solution approaches were considered. The surveyed preferences for the areas are topic-specific and cannot be generalised. Nevertheless, for the chosen topics the initial results of this study show that the implementation of solution approaches to promote constructive hope, as proposed by Grund and Brock (2019) and Ojala (2012), is also demanded by the students.

The analysis on the topic emotions and their changes alongside the (different) interventions still needs to be carried out. Furthermore, in order to answer RQ2, data from a second study will be obtained and analysed.

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Exploring Students' Conceptions Of Critical Raw Materials And Their Availability

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Critical Raw Materials (CRMs) are essential for clean-energy technologies, yet their supply is often vulnerable due to import dependencies, geopolitical conflicts, and socio-environmental constraints. Although policy initiatives such as the EU Critical Raw Materials Act address these challenges, public awareness remains limited, highlighting the need for education. While existing science education projects provide valuable learning environments addressing CRMs, less is known about how students conceptualize the availability of CRMs prior to instruction. This study is embedded in the educational research of the Collaborative Research Center (CRC) "Iron, upgraded!" and follows the Model of Educational Reconstruction (MER). Focusing solely on the learner perspective in this article, we investigate students' conceptions of the availability of CRMs. A preliminary survey (N = 295) on associations with the term "critical raw material" indicated that students primarily approach the topic in a problem-oriented way, while also referencing dimensions of criticality such as scarcity and importance. Subsequently, guideline-supported interviews with 12 upper secondary school students were conducted and analysed using qualitative content analysis. Five conceptions regarding the availability of CRMs emerged: supply constraints due to (i) low geological availability, (ii) geopolitical instability, (iii) low ecological and social acceptance, (iv) demand growth, and (v) limited technological accessibility. Results suggest that students predominantly interpret availability through a finite-stock mental model, while geopolitical, socio-ecological, technological, and demand-related dimensions are less spontaneously integrated and may require contextual prompts. These insights provide starting points for MER-based instructional design and point to opportunities for linking criticality to mitigation strategies such as substitution.

Keywords: Conceptual Understanding, Sustainability, Critical Raw Materials

Introduction

Critical Raw Materials In The Energy Transition

In response to the global climate crisis, a shift towards a post-fossil society with a sustainable energy system is essential. However, this transition requires substantial amounts of raw materials needed for deploying clean energy technologies. For instance, EU demand for lithium is expected to increase twelve-fold by 2030 and twenty-fold by 2050 (European Commission, 2024). Yet, many of these raw materials are either not found in Europe or are not mined in sufficient quantities. Consequently, the EU relies heavily on imports, often from geopolitically unstable regions or single-source suppliers (European Commission, 2023). Without coordinated action, the European climate goals are at risk (European Commission, 2024).

To address these challenges, the concept of Critical Raw Materials (CRMs) has gained prominence (European Commission, 2011; Graedel et al., 2012; NRC, 2008). CRMs lack a universally agreed definition because criticality varies by time, country, and context. However, it is broadly understood as the likelihood and potential consequences of a supply disruption (Schrijvers et al., 2020). Accordingly, the EU describes CRMs as materials of high economic importance while also being highly vulnerable to supply disruptions (European Commission, 2011). Initiatives such as the EU's Critical Raw Materials Act aim to secure these materials to meet the 2030 climate and digitalization targets (European Commission, 2024). Nevertheless,

public awareness of CRMs and their role in the energy transition remains limited, making education and communication essential (Kot-Niewiadomska, 2022).

Critical Raw Materials In Science Education

Several EU-funded projects address the educational gap around raw materials and sustainability. For example, the "Young Raw Material Ambassadors" program equips students aged 10 to 18 with knowledge about raw materials through interactive tools such as digital serious games (Torreggiani et al., 2021). Gullón Corral et al. (2023) developed the "Briefcase Project", a hands-on teaching kit highlighting mineral properties, societal impacts, and the role of raw materials in everyday life. Beyond these EU projects, Huwer et al. (2022) created digital learning environments for chemistry education incorporating augmented reality to explore elements in everyday devices and their recyclability. Bütow and Eilks (2023) developed a digital learning environment designed to integrate CRMs into chemistry curricula and subsequently evaluated its implementation by comparing German high school students with U.S. undergraduate chemistry students (Bütow et al., 2025).

While these projects provide valuable resources, a research gap remains concerning students' conceptions of critical raw materials, especially regarding what "availability" means and what learners intuitively consider as causes of scarcity. Such insights could be beneficial for designing learning environments that connect to learners' existing ideas and support conceptual development.

Motivation And Theoretical Framework

This study is embedded in the educational research subproject WIKO (German abbreviation for *Wissenschaftskommunikation*, i.e., science communication) of the Collaborative Research Center (CRC) "Iron, upgraded!" (www.chemie.tu-darmstadt.de/iron-upgraded/index.en.jsp), which investigates how iron's reactivity and selectivity can be controlled so that iron-based compounds can substitute rare, toxic, expensive, or critical metals in key technological applications, such as fuel cells and magnets. A key aim of the WIKO project is to support learners in understanding the relevance of CRMs and the idea of material substitution (e.g., iron-based solutions as potential alternatives to scarce or geopolitically sensitive materials in specific applications).

The study follows the theoretical framework of the Model of Educational Reconstruction (MER), which emphasizes the interconnection of reconstructed scientific content and students' pre-instructional conceptions to foster meaningful learning (Bliesmer & Komorek, 2023; Duit et al., 2012). MER highlights the importance of acknowledging students' perspectives and aligning them with scientifically accurate concepts (Komorek & Kattmann, 2008). This approach, rooted in conceptual change theory, is particularly effective when students' fragmented and context-dependent knowledge is incorporated into instructional design (diSessa & Sherin, 1998; Treagust & Duit, 2008).

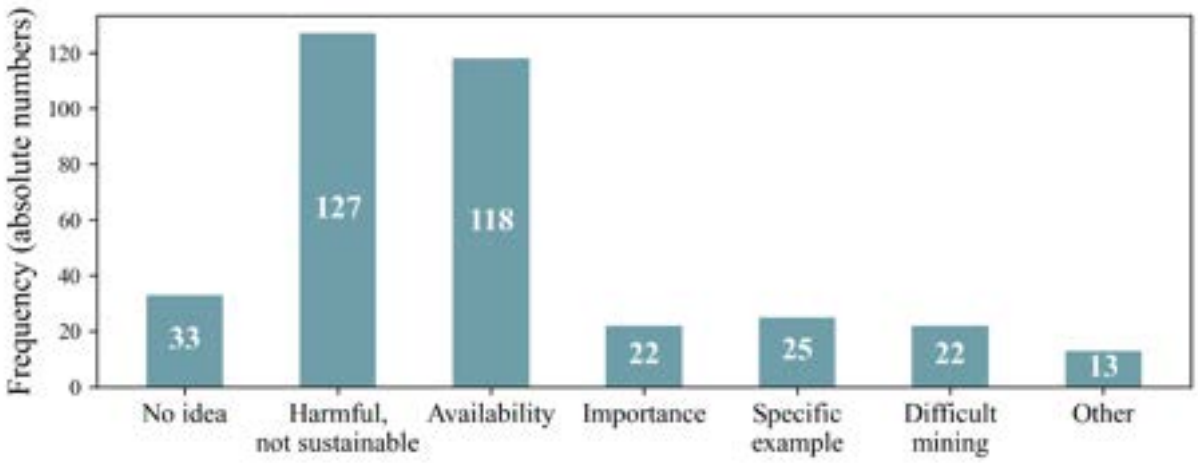
MER comprises three perspectives: (i) the investigation of scientists' conceptions, including the analysis and structuring of scientific content, (ii) the investigation of learners' conceptions, and (iii) the design or evaluation of a learning environment. **The present contribution focuses only on the learner perspective.** It therefore provides a targeted overview of how learners think about the availability of critical raw materials, rather than reporting a complete MER cycle. We address the following research question: What conceptions do upper secondary school students hold about the availability of critical raw materials?

Preliminary Study: Students' Associations

Starting the investigation into learners' perspectives, we first explored whether the term "critical

raw material" is sufficiently present in students' thinking to justify in-depth qualitative exploration. Accordingly, we conducted a preliminary quantitative survey asking: "What do you associate with the term 'critical raw material'?" (Prechtl et al., 2025). To ensure data quality, we excluded responses that were incomplete or showed signs of insufficient engagement, specifically those where the processing time fell below the threshold of 10 seconds per survey page. After this, a final sample of N = 295 responses remained. We then coded and grouped the open responses thematically and visualized their absolute frequencies to identify the most common associations (see Figure 1).

Figure 1. Frequency of thematically coded open-ended responses to the question "What do you associate with the term 'critical raw material'?" (Prechtl et al., 2025).



In Figure 1, two observations stood out. First, students approached the topic in a strongly problem-oriented way. A large share of responses related to environmental harm and non-sustainability, indicating that students tend to frame CRMs primarily through consequences and risks. Second, many responses also referenced aspects that align with the formal notion of criticality, such as availability/scarcity and the importance of raw materials. Overall, the framing and the low number of the "no idea" category suggested that the concept is present enough in students' thinking to justify a deeper exploration of how they interpret the term.

Methods

We conducted guideline-supported interviews with open-ended questions and clarifying interventions. The study included 12 upper secondary school students (mean age: 17.75 years; 7 females, 5 males) from three schools in Hesse, Germany, who participated voluntarily in summer 2023. To support an open atmosphere, interviews were conducted in a conversational setting. The average interview duration was 64.2 minutes. The content validity of the interview questions was supported using the collect, check, sort, and subsume approach, complemented by a pilot test with two students to improve clarity and understandability. Interviews included opportunities for clarifying interventions when students' meanings required further elaboration or when relevant dimensions of availability did not emerge spontaneously. Data were analysed using adapted methods of qualitative content analysis (Gropengießer, 2008) to identify and categorize students' conceptions. Audio recordings were transcribed verbatim. Relevant statements addressing the research question were systematically coded and similar statements were grouped to form categories. To support the quality and consistency of the analysis, category definitions, anchor examples, and coding rules were reviewed iteratively (Mayring, 2022). The validity of results was further supported by comparing emerging conceptions with published studies on related topics. Initially, the German interview transcripts were analysed, and relevant statements were then translated to illustrate students' conceptions.

Selected Results

The analysis revealed five distinct conceptions regarding the availability of critical raw materials (Table 1).

Table 1. Students' conceptions of CRM availability.

	Students' conceptions	Example statements
1	Supply constraints due to GEOLOGICAL AVAILABILITY	"By scarce, I mean that the raw materials do not occur in sufficient quantities." (Amira)
2	Supply constraints due to GEOPOLITICAL INSTABILITY	"The countries where the raw materials come from are not necessarily always politically stable countries. This means that conflicts can arise there that can spill over into the economy." (Amira)
3	Supply constraints due to ECOLOGICAL AND SOCIAL ACCEPTANCE	"The mines are harmful to the environment and I can imagine that people don't want them in their neighborhood." (Sarah)
4	Supply constraints due to DEMAND GROWTH	"Population growth is connected to the raw material consumption. […] the global demand is rising, which means that there isn't enough for each individual country." (Chiara)
5	Supply constraints due to TECHNOLOGICAL ACCESSIBILITY	"Other deposits may then be very difficult to mine." (Chris)

Nearly all students associated scarcity primarily with geological availability. In their explanations, terms such as "rare", "scarce", and "available" referred to whether sufficient reserves of specific raw materials exist. Conception 1 (GEOLOGICAL AVAILABILITY) captures the view, that scarcity primarily reflects limited geological occurrence, i.e., insufficient quantities of raw materials being available in the nature. Accordingly, students often conceptualized availability as a largely fixed physical quantity and assumed that limited occurrence directly translates into limited supply. Some even described a depletion narrative, suggesting that continued extraction could ultimately lead to absolute exhaustion of resources. For example, one student stated: "There will simply be no more raw materials" (Mia).

Conception 2 (GEOPOLITICAL INSTABILITY) addressed geopolitical conflicts as a cause of supply constraints. For many participants, this perspective became more explicit after interventions concerning Europe's import dependency. Students argued that European countries such as Germany rely strongly on political and economic relations with supplying countries, which can be problematic when these relations deteriorate. Moreover, students highlighted that these dependencies are not only a passive vulnerability but can be used deliberately as a source of leverage. One student, for example, described the risk of supply being intentionally restricted in the context of geopolitical conflicts:

> "If China ends up in a major conflict with the EU and decides to say, 'No, you won't get any rare earths from us anymore,' that poses a significant risk because they hold nearly 100 percent of the market share" (Chris).

All students addressed environmental and social consequences of mining and frequently framed these impacts as a possible dimension of critical raw materials. However, only about half of the participants explicitly linked these concerns to availability constraints. Conception 3 (ECOLOGICAL AND SOCIAL ACCEPTANCE) describes the idea that supply limitations may result from low ecological and social acceptance of mining activities. Students argued that mining can cause severe environmental harm and social conflict, which may lead to public resistance, stricter regulation, or even the closure of mining sites. In this view, raw materials may be geologically present, yet effectively "unavailable" because extraction is contested or considered unacceptable.

Many students described scarcity as a function of rising demand. Conception 4 (DEMAND GROWTH) captures the ideas that a continuously increasing demand will eventually surpass an already limited geological supply. Students explained demand growth through drivers such as population growth and technological developments. In particular, some learners referred to the energy transition and the expansion of modern technologies as increasing the need for specific raw materials. One student exemplified this by linking battery technologies to future supply challenges: "For instance, lithium, which is essential for batteries, is relatively scarce. Expanding its use on a global scale will make the supply problematic" (Sebastian).

Some students additionally mentioned the technological accessibility of raw materials. Conception 5 (TECHNOLOGICAL ACCESSIBILITY) describes the idea that raw materials may become scarce because certain deposits are increasingly difficult to exploit. However, students' ideas were inclined to focus on the assumption that easily accessible deposits will eventually be exhausted. As a result, extraction would require more complex technologies or become less feasible.

Discussion

The prevalence of Conception 1 (GEOLOGICAL AVAILABILITY) indicates that students predominantly frame raw materials criticality as a problem of "how much exists". This perspective resembles an intuitive "running-out" narrative: resources are treated as a fixed stock that steadily declines with use. In contrast, scientific discussions of raw material availability emphasize that absolute geological scarcity is unlikely to constrain access to most materials in the foreseeable future, because what is considered as economically recoverable reserves changes with exploration, technology, and market conditions (Coulomb et al., 2015). From this standpoint, students' focus on depletion may obscure more relevant drivers of criticality such as supply concentration or geopolitical and socio-ecological constraints (Schrijvers et al., 2020). For instructional design, this suggests a need to explicitly differentiate the terms "resources" and "reserves", and show that both are not fixed but dynamic socio-technical concepts.

The students' ideas regarding Conception 2 (GEOPOLITICAL INSTABILITY) are broadly aligned with established CRM logic: import dependency can create vulnerability, and exporting countries may use supply restrictions as political leverage (Nuss et al., 2016). However, the fact that this conception often became salient only after interventions suggests that geopolitical supply risk is not an everyday idea for many learners and requires contextual cues (e.g., a map of Europe's import structure of raw materials) to be activated. This pattern fits well with a "knowledge-in-pieces" interpretation (diSessa, 2018): students may possess relevant fragments (e.g., "conflicts disrupt trade"), but these pieces are not reliably triggered without situational prompts. For teaching, this implies that geopolitical considerations need structured support such as supply-chain mapping or scenarios that make dependencies visible.

Conception 3 (ECOLOGICAL AND SOCIAL ACCEPTANCE) reflects a shift from purely physical

understandings of availability toward socio-environmental conditions that shape whether extraction can occur. Students' arguments resemble a "not in my backyard" logic: mining might be technically possible, yet effectively blocked by regulations or concerns. Notably, while these sustainability impacts were widely recognized, only about half of the students explicitly connected them to availability constraints. This suggests that learners often treat ecological/social harm as a separate "problem of mining", rather than as a factor that can restrict supply. In instructional terms, this indicates a learning need to explicitly link these ideas to the notion of availability.

Students' reasoning regarding Conception 4 (DEMAND GROWTH) resembles a scaling heuristic: more people and broader deployment of technologies imply more consumption, which eventually overwhelms supply. This is a plausible everyday schema and can serve as a productive starting point. At the same time, students' accounts were inclined to model supply as essentially static and demand as continuously rising, often without considering counteracting dynamics (e.g., efficiency gains, substitution, recycling). In this sense, Conception 4 parallels Conception 1: scarcity is again framed as a largely inevitable trajectory toward shortage, rather than as a system shaped by technological, economic, and political choices. From a reconstruction perspective, instruction could build on this intuitive logic but broaden it with mitigation strategies.

Conception 5 (TECHNOLOGICAL ACCESSIBILITY) expands availability beyond geology by introducing technological accessibility. However, students' ideas often remained tied to a simplified narrative: high-grade or near-surface deposits are exhausted, therefore extraction becomes more difficult. This captures an important aspect of accessibility but remains underspecified. Moreover, scientific criticality assessments highlight additional mechanisms that were not present in the students' accounts, such as by-product dependency, where production depends on the mining of the host metal (Nassar et al., 2015). For instructional design, this suggests expanding the ideas of "harder mining" with aspects of refining, co-production, by-product dependency, and processing bottlenecks.

Limitations

This study is based on a small qualitative sample from three German high schools and thus does not aim at statistical generalization. At the same time, the qualitative findings are complemented by the preceding survey (N = 295; Prechtl et al., 2025). Across both datasets, students' responses consistently foreground scarcity-related reasoning, providing converging indications of the prominence of a "running-out" narrative and a primary focus on scarcity and depletion. Therefore, these results should serve to identify possible starting points and to derive instructional guidelines for teaching the concept of CRMs. However, the learning environment developed later should be evaluated for its suitability to foster an adequate understanding of the availability of CRMs.

Conclusion

This paper provides an overview of learners' perspectives on CRM availability. Overall, the results suggest that students primarily interpret the availability of critical raw materials through a finite-stock mental model: scarcity is understood as a direct consequence of limited geological occurrence and ongoing extraction. While students are able to articulate dimensions of supply risk, these additional dimensions appear less spontaneously integrated into their initial reasoning and, in some cases, required contextual interventions. From a MER perspective, this points to fragmented, context-dependent knowledge rather than a consolidated, multidimensional understanding of criticality. Building on these entry points, the MER framework can guide the development of learning pathways that explicitly frame availability as a multidimensional concept and address common intuitive ideas such as the "running-out" narrative.

Outlook

In subsequent MER steps, the instructional guidelines derived from the present findings will be translated into an experimental learning environment in the CRC "Iron, upgraded!" context. It will utilize the case of substituting a critical platinum catalyst by an iron-based alternative in fuel cells to connect raw materials criticality to concrete mitigation strategies and their trade-offs.

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ESERA 2025 Copenhagen

Sustainable Competencies In Education: Building Curricula And Advancing Teacher Training Together

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Sustainable development offers a pathway to address humanity's greatest challenges such as climate change and biodiversity loss. However, current science curricula often fall short in adequately preparing students to address these complex issues. At ESERA 2025, we held an exploratory seminar addressing this gap by focusing on the interdisciplinary nature of Education for Sustainable Development (ESD) and developing ideas for effective curricula and empirical studies. We discussed two key questions: 1) How can we better prepare teachers to teach sustainability competencies? and 2) Which empirical studies are most informative for designing curricula to teach sustainability competencies?

In this text, we first describe a course for educators on integrating ESD in their lectures at a technical university. We used insights from this course to design the exploratory seminar for ESERA 2025. Then we describe the structure of the exploratory seminar, in which participants engaged in a grouped think-pair-share activity to collect ideas to answer the key questions. This was followed by short presentations from group representatives in a plenary discussion. Finally, we summarize the discussion to inform future curriculum development and research initiatives.

Keywords: Education for Sustainable Development; Competencies; Curriculum Development

Introduction: Education For Sustainable Development (ESD)

Sustainable development is such a central political goal that, in some countries, it is enshrined in the constitution (e.g., in Switzerland, Art. 2 & Art. 73; Bhutan, Art. 5; partially also in Ecuador, Art. 14). The way to achieve this goal can be informed by science. Scientifically based mitigation strategies involve a reduction of emissions at the individual and global levels (Wynes & Nicholas, 2017). In schools, however, such mitigation strategies are rarely discussed, or if so, they focus on private-sphere actions (Kranz et al., 2022). When economic alternatives such as degrowth are mentioned, this is done only sporadically or decontextualized (Díez-Gutiérrez et al., 2024). System-critical questions are rarely addressed, which led Huckle (2012) to conclude that "Mainstream ESD […] uncritically embraces economic growth, globalization and consumerism" (Huckle, 2012, p. 366).

On the other hand, ESD and sustainability competencies are increasingly included in curricula as educational goals. The goal is to prepare students for an unknown future. Many competence frameworks require students to obtain competencies in sustainable development. For example, in Switzerland, the framework curriculum for high schools, such as the Gymnasium, wants students to achieve a deepened social maturity. Such a deepened social maturity requires, among other things, networked, interdisciplinary thinking and education for sustainable development (Schweizerische Konferenz der Kantonalen Erziehungsdirektoren, 2023). As a result, there is a mismatch between current educational practices and the desired outcomes. This warrants research to identify the barriers to changing current practices and to develop effective curricula for ESD.

How should effective ESD curricula be implemented? Whereas it is desirable that ESD includes those strategies that are scientifically backed up to mitigate climate change, ESD must follow certain principles to be ethically valid. The Beutelsbacher Consensus (Wehling, 1977) prohibits instrumental education. It emphasizes that students should develop competencies to form independent opinions rather than being indoctrinated. For example, ESD must not educate pupils 'for' degrowth. On the other hand, the Beutelsbacher Consensus also mandates the inclusion of

diverse viewpoints, including those unfamiliar to students, to promote reflective thinking and avoid indoctrination through omission. Paradoxically, this turns the current practices of rarely mentioning alternatives to the current system (see Díez-Gutiérrez et al., 2024) into a form of indoctrination.

The Role Of Science Education

Every subject in science education has inherent links to sustainability: From the chemical basis of the carbon cycle or processes of material corrosion, the physics of climate change, the geographical impact of human activities, the biological damage of biodiversity loss, to the mathematical modelling of exponential growth. These links provide a foundation for interdisciplinary discussion of mitigation strategies. However, this requires that teachers are prepared to link sustainability issues to their subject and to promote sustainability competencies.

To address this need, the following sections describe an exemplary course designed to support university faculty in integrating ESD into their curricula. This course served as the inspiration for our seminar, as the experiences and pedagogical gaps identified during its implementation directly inspired the research questions and organizational structure of the exploratory seminar held at ESERA 2025. Following the description of this course, the method section details the structure of the ESERA seminar itself. We then present the results derived from that seminar and conclude with a discussion and an outlook for future research.

An Example Course

We developed a course on ESD for university educators at a technical university. The course is divided into three parts: a digital self-study activity, an in-person workshop, and an implementation phase.

Self-Study Activity

In the self-study activity, educators complete a learning module on an online platform. The module starts with a quiz as a formative assessment that also activates prior knowledge about the topic and uses pretesting effects to convey information (Pan & Carpenter, 2023). Afterward, they work through videos and texts describing the climate crisis, the idea of sustainability, and how sustainability relates to ecology, society, and economy. Afterward, to support educators in drawing connections to their teaching, we present the Sustainable Development Goals (SDGs). Using the wedding-cake depiction (see Figure 1), we draw the connection between the three pillars of sustainability (ecology, society, and economy) and cluster the 17 SDGs. The SDGs help as a framework to conceptualize sustainability from different perspectives. All educators should then identify 1-3 SDGs that relate to their teaching. Finally, they also need to formulate a teaching goal.

In-Person Workshop

The in-person workshop starts with thought-provoking quotes about sustainability and an introduction of the participants. Then we discuss the result of the quiz, highlighting questions where participants had a lot of prior knowledge as a motivation, and those questions where participants answered mostly incorrectly. We also repeat core concepts around the problem, such as the 1.5-degree goal, the tipping points, and the relation of energy use, economic growth, and emissions.

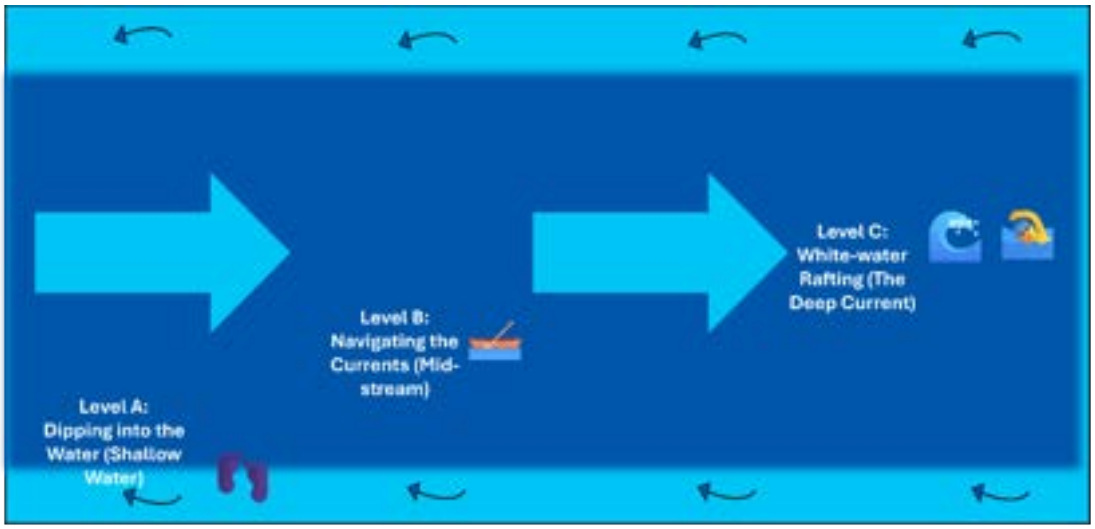
Figure 1. Wedding cake depiction of the Sustainable Development Goals.



Credit: Azote for Stockholm Resilience Centre, Stockholm University CC BY-ND 3.0. Reproduced with permission.

To encourage educators to reflect on the extent to which they want to integrate sustainability in their teaching, we utilize the metaphor of fluid spaces, specifically as a river (adapted from Bellina et al., 2018). This metaphor categorizes ESD engagement into three levels, as illustrated in Figure 2. At Level A) on the riverside, they could dip their feet into the water to gain initial experience of teaching sustainability issues, e.g., by adding a few teaching or learning situations related to sustainability. At Level B) they start navigating the currents. Thus, they could create a stronger focus on sustainable development by having dedicated learning goals and cross-referencing between topics that relate to sustainability. At Level C) they engage in white-water rafting in the middle of the river. There, they completely adapt their teaching toward sustainability.

Figure 2. River metaphor of integrating ESD in one's teaching.



Every level comes with challenges: At Level A) we refer to a river-swimming experience from outdoor education (Thurn et al., 2025), where in shallow waters, there is a strong eddy flowing upwards. That is, in shallow waters one is literally swimming upstream. We use this analogy, to vividly explain what could happen when educators add a single activity on sustainability and disregard it in other contexts. Such small actions might evoke the image of greenwashing or lead to rebound effects, such as the perception that sustainability is already discussed once and does not need further attention. In the literature, this is discussed as single-action bias (Zhao & Luo, 2021). It is not wrong to start with baby-steps when changing one's lecture, but one needs to be

aware of such countermovements. At Level B) teaching the complexity of the climate crisis and sustainability in relation to one's lecture topics might become overwhelming for teachers and students. It might also lead to strong reactions by students, who do not see a connection. At Level C) it will become clear that sustainable development comes with lots of ambiguity. It will also be relevant to discuss one's own personal behaviour with regard to sustainability here at the latest.

In the workshop, educators reflect on the different levels and decide at which level they want to implement sustainable development in their lecture. We assign them to groups that aim for the same level, as these groups face similar challenges. During a group activity in the form of a collegial coaching, educators present their lecture and explain which SDGs it covers and how the content relates to sustainability. They present their learning goal and how they will include it in their lecture. The other group members listen and ask themselves: Where do you see chances and risks in the plan? Then they exchange ideas before moving on to the next person presenting their lecture. In a consolidation phase with all participants, each group summarizes its discussion. We then discuss how to deal with frequently mentioned challenges such as emotions (solastalgia, Albrecht et al., 2007; climate change anxiety, Clayton, 2020), rebound effects (e.g., Colmenares et al., 2018), or the single action bias (e.g., Zhao & Luo, 2021).

Implementation And Reflection Phase

In the last phase of the course, educators work on their plan for how to include sustainability in their teaching. During the next weeks, they implement their plan. Afterward, they write a short reflection reporting what their learning goal was and how it went.

Experiences From The Course

A takeaway from the course was the effectiveness of think-pair-share activities (e.g., Kaddoura, 2013). Think-pair-share activities transcended simple classroom participation, often into a form of collegial coaching. By allowing educators to first reflect individually, we cognitively activated them. The share phase led to peer-to-peer support, discussing the complexities of teaching across disciplines.

The course also revealed two areas where even motivated educators lacked important concepts: Whereas most participants were familiar with the ecological footprint, there was a lack of awareness regarding the ecological handprint. The handprint focuses on positive actions that reduce the footprints of others and is a crucial motivator for ESD (Kühnen et al., 2019). Furthermore, there was a gap in understanding the tipping points. Participants often had not heard of this concept or viewed climate change as a linear progression.

The Exploratory Seminar At ESERA

Derived from the research desiderata described above, and the experiences we gained through giving a course on sustainability integration for educators, we aimed to work on the following questions in the exploratory seminar at ESERA 2025:

1) What barriers exist in implementing ESD curricula, and how can these be overcome?

2) How can we better prepare pre-service teachers to teach sustainability competencies?

3) Which empirical studies are most informative for designing curricula to teach sustainability competencies?

At the beginning of the seminar, we introduced these key questions and explained the structure of the seminar. In the setting of a grouped think-pair-share activity, attendees would share their views on these questions. To foster exchange and the documentation of the results, we asked that each group presents its results to the plenum at the end. Attendees could join one of the three

groups to address one of the questions. As participants favored questions 2 and 3, we did not discuss the first question in the seminar. For the sake of completion, we thus cover this question in the discussion section, where we summarize key barriers identified by scientific studies.

In the groups, attendees followed a think-pair-share activity. In the first step, they had individual time to think about answers to the respective questions. Afterward, attendees paired with their group members to discuss how they might contribute to solving their group's question.

In the share phase, all groups came together to exchange their developed ideas and receive feedback from all other attendees. The aim was to arrive at specific ideas for promising next steps in this research area. These could include collaborative research projects, theoretical or empirical research papers, or the establishment of discussion groups to continue working on the ideas after the conference.

Results From The Exploratory Seminar

Here we present the aspects that participants discussed in the exploratory seminar at ESERA 2025 regarding the two questions.

How Can We Better Prepare Pre-Service Teachers To Teach Sustainability Competencies?

Participants emphasized that teachers require tools to facilitate difficult classroom discussions. These conversations often involve navigating high levels of tension. This requires teachers to be prepared to handle the intense emotions students bring to these topics. To address this, participants specifically recommended the Climate Emotion Wheel (Pihkala, 2022, 2024). This tool serves as a reflective framework, helping teachers anticipate and categorize the wide variety of emotional responses—ranging from anxiety to empowerment—that sustainability topics can trigger.

Participants also highlighted the importance of experiential learning. They advocated for place-based education that increases immersion and nature connectedness. Place-based education grounds lessons in local environments to make abstract concepts tangible (Smith, 2013). Outdoor, project-based education is suitable for place-based education (Thurn et al., 2025). Nature connectedness is the subjective connection to nature (Capaldi et al., 2014). It describes one’s personal relationship with the natural world, and studies showed that it is a strong predictor for environmental action (Nisbet et al., 2009). Participants also named public speakers and non-profit associations that could serve as resources for teachers.

Finally, participants underscored the necessity of providing teachers with a comprehensive understanding of the sustainability competencies specific to their regions. This includes clarity on the frameworks that are used, the rationale behind why specific competencies were selected, the relevance of these competencies, and their integration into existing curricula. By analysing how different countries embed sustainability into their educational systems, teachers can establish a collective understanding of the topic. Participants termed this blend of subject expertise and teaching strategy as Pedagogical Content Knowledge (PCK) about sustainability.

Which Empirical Studies Are Most Informative For Designing Curricula To Teach Sustainability Competencies?

Participants emphasized the importance of defining sustainability competencies to ensure that they are practically applicable in educational settings. For example, useful frameworks exist, such as the Sustainable Development Goals (SDGs), the framework of Wiek (2011), or the European Green Competence Framework. However, in competence-based education, there is a challenge of teaching and assessing such competencies.

A central goal of competence-based education is the development of action-competence, which moves beyond passive knowledge toward the willingness and ability to take actions. To achieve this, a research desideratum exists regarding the professionalization of teachers. Educators require more sophisticated tools to navigate the complex landscape of emotions and norms that sustainability topics inevitably evoke. This includes developing specific strategies for dealing with controversy and facilitating meaningful climate action while maintaining pedagogical integrity. Whereas the participants did not name specific further tools for these dialogues, current research highlights approaches for dealing with emotions. For instance, Finnegan and d'Abreu (2024) argue for the integration of hope (see also Grund & Brock, 2019), while Ranney and Velautham (2021) point toward socio-emotional and social justice education as essential foundations for managing complex topics.

The participants also mentioned the necessity of more diverse and robust methodological approaches to better understand how these competencies are acquired. Participants suggested mixed methods designs and multi-lab studies to address the cultural diversity inherent in global environmental challenges. This could help identify universal versus context-specific educational strategies. It is equally vital that research investigates the progression of ESD across all age groups, which stretches from the early foundations in kindergarten all the way through to higher education.

A recurring challenge that participants named in relation to this is how to effectively connect the local with the global, a concept often referred to as the 'glocal' approach. The idea of glocal is that by rooting global sustainability issues in local contexts, educators can increase the personal relevance of the material for their students. Studies could examine how such approaches can incorporate intergenerational aspects, enabling students to see how their current local actions impact both their own future and the global community at large.

Discussion

What Barriers Exist In Implementing ESD Curricula, And How Can These Be Overcome?

As we did not cover this question in the exploratory seminar, we describe key findings from the literature here. Borg and colleagues (2012) list a lack of examples and a lack of expertise as frequent barriers. Pompeii and colleagues (2019) report a detailed list of teacher-identified barriers, with the most frequent being discipline restrictions and personal priorities. They also list student-identified barriers. Disciplinary silos and a lack of adequate professional training opportunities also appear in Parry & Metzger (2023). The barriers thus seem to revolve around a factor comprising lack of "know-how", including best-practice examples and trainings on the topic, and a factor related to the perceptions of one's discipline. Ways to overcome these barriers seem easier to implement for the first factor. More resources, such as professional training, lists of successful examples, or exchange with colleagues, could provide teachers with more ideas in implementing ESD curricula.

Conclusion

In this text we have discussed three key questions regarding the progress of ESD. For the question of existing barriers, the literature revealed that teachers lack the know-how and see discipline restrictions. In the exploratory seminar, participants' answers revealed that to prepare teachers better to teach sustainability competencies, we need to equip them with better Pedagogical Content Knowledge on ESD. This includes how to navigate emotions and norms. It also includes preparation to design experience-based instruction. For the question of informative empirical studies for the design of ESD curricula, participants' answers revealed that such studies should investigate effective strategies for dealing with controversy and emotions.

In conclusion, with a strong foundation in literature on ESD, we identified key areas to guide future research and curriculum design. Integrating these areas into teacher-education programs can enhance the preparation of teachers for building sustainability competence in their profession.

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ESERA 2025 Copenhagen

‘How Sustainable Is ...?’ A Teaching Approach In The Field Of Education For Sustainable Development

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Science education can make an important contribution to supporting the 17 Sustainable Development Goals of the United Nations through Education for Sustainable Development (ESD). The paper describes the development of the teaching approach ‘sustain.able?!’ within the framework of design-based research. The approach implements ESD into science lessons by enabling students to systematically assess controversies (e.g. bio-based plastics, vegan diet) considering the three dimensions of sustainability environment, economy and society. At the core of the teaching approach are the so-called 'AssessmentBubbles'. These contain information on the respective controversy, which the students assess from different perspectives based on specific criteria. The assessments are then recorded and reflected on an AssessmentDisc by Banse & Marohn (2021, 2022). This paper outlines the development of the method AssessmentBubbles within the framework of two research cycles involving 46 teachers, 12 experts and 17 students. A trial using the example of vegan diet with 28 students (aged 14-15) shows that the AssessmentBubbles method enables students to assess information from multiple perspectives in terms of sustainability and that they evaluate the method positively.

Keywords: Sustainability, Education for Sustainable Development, design-based research

Introduction

We encounter sustainability in many areas of everyday life, from food shopping and clothing to mobility. Schools should therefore play a key role in showing students the many facets of sustainability, while also promoting their ability to make judgements and take action in this context. But how can learners assess the sustainability of controversies based on criteria?

One possible approach is offered by the teaching approach *nachhaltig.bewerten (assessing sustainability)* which enables students to assess the sustainability of controversies (e.g. *electromobility*) from multiple perspectives (Banse, 2025; Banse & Marohn 2021, 2022). Furthermore, it provides three *AssessmentLevels* (space, time and group) to guide the assessment process systematically. The *AssessmentDisc* enables a didactically reduced conclusion about the sustainability of the controversy.

Although the teaching approach has been successfully tested (Banse, 2025) there is still room for improvement, especially in terms of supporting the students during the assessment process. The teaching approach *sustain.able?!* presented below is a further development of the approach *nachhaltig.bewerten*, which aims to bridge existing research gaps.

Theoretical Background

Sustainability

The guiding principle for sustainable development, published in 1987 by the United Nations World Commission on Environment and Development, states that development is considered sustainable if it ‘meets the needs of the present without compromising the ability of future generations to meet their own needs’ (World Commission on Environment and Development, 1987, p. 16). The Agenda 2030 adopted by the United Nations contains 17 Sustainable Development Goals and expresses the multifaceted nature of sustainability. Thus, it points out that sustainable development cannot only focus on the environment (United Nations, 2015).

Instead, it raises the question of how development can be organized to be ecologically compatible, economically efficient, and socially fair, while enabling current and future generations to lead a good life (MSB NRW, 2019).

This understanding of sustainability with its dimensions of *environment*, *economy* and *society* form an important basis for the teaching approach.

Education For Sustainable Development

Global education systems are also important for the realization of sustainable development. The global UNESCO programme 'Education for Sustainable Development, ESD 2030' emphasises the importance of ESD for achieving the Sustainable Development Goals (Bundesministerium für Bildung und Forschung, n.d.). Education for Sustainable Development should empower children and young people to take responsibility for shaping their own future and that of their generation in line with the principles of sustainable development (UNESCO, 2020).

The school should provide students with the necessary subject-specific and interdisciplinary skills to help them judge and act on important future issues (MSB NRW, 2019). In Germany, ESD is regarded as an important part of school education and is anchored as a mandatory cross-cutting topic in all subjects (ibid.). The teaching approach integrates ESD into the students' learning process.

The Basis Of The Teaching Approach *sustain.able?!*

The teaching approach presented in this contribution is based on the approach of *nachhaltig.bewerten* by Banse & Marohn (2021, 2022), which will be outlined briefly below.

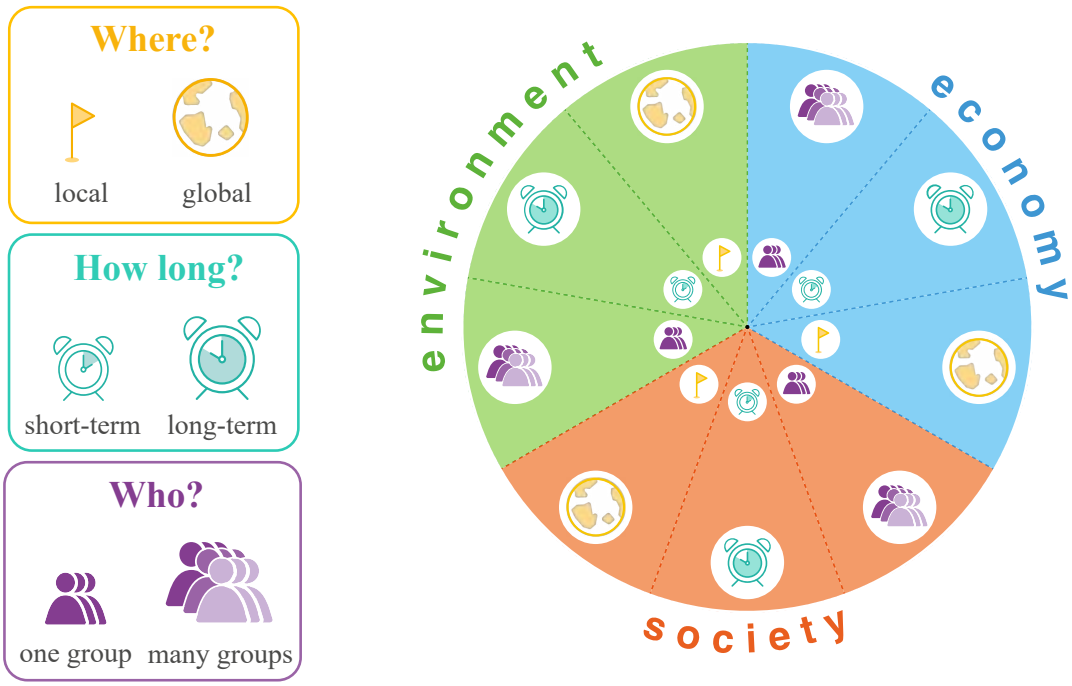
The teaching approach enables students to assess controversies in the context of sustainability based on criteria, taking into account the three dimensions of *environment*, *economy* and *society*.

The process of assessment involves the *AssessmentLevels* of space, time and group (Figure 1, left). When students ask whether a controversy such as the expansion of electromobility is beneficial or harmful to sustainability, they can consider it on these three levels of assessment. *Where* are the benefits or harms visible – only locally, e.g. in one city or globally, all over the world? *How long* do the benefits or harms last – are they only short-term, affecting those living today or long-term affecting future generations? *Who* benefits or suffers harm – just one group, such as farmers, or many groups? The teaching material on the controversy surrounding *electromobility* includes, for example, the information that electric cars emit less CO_2 than cars with combustion engines. This describes a *global*, *long-term* impact that affects *many groups*.

The methodological tool used to structure the assessment process is the *AssessmentDisc* (Figure 1, right), which combines the *AssessmentLevels* with the sustainability dimensions *environment*, *economy* and *society*. The *AssessmentDisc* thus visualizes that the questions about *where*, *how long*, and for *whom* a controversy has a beneficial or harmful effect can arise within all sustainability dimensions. When assessing information relating to a controversy, students can mark the corresponding symbols of the *AssessmentLevels*: green for a benefit and red for a harm.

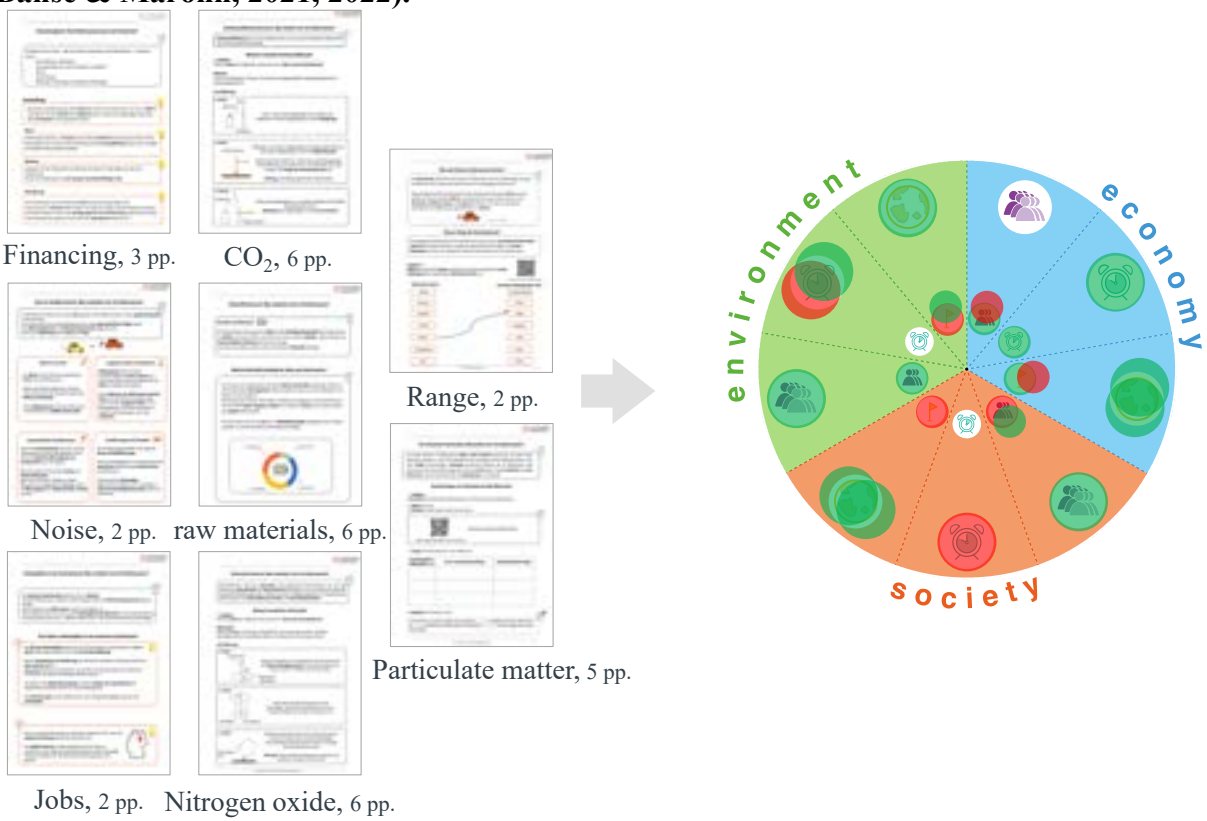
The example just mentioned regarding the reduction of CO_2 emissions describes a *benefit* provided by electric cars. Accordingly, the three *AssessmentLevels* affected – *global*, *long-term*, and *many groups* – are marked *green* on the *AssessmentDisc*. The green markings on the *AssessmentDisc* are in the area of the *environment*, as the information can be assigned to this sustainability dimension.

Figure 1. AssessmentLevels (left) and AssessmentDisc (right) (Banse & Marohn, 2021, 2022).



In order to assess the sustainability of a controversy (here: *electromobility*) the students first work out comprehensive information on various aspects of the controversy (e.g. CO_2 emissions, noise pollution or raw material extraction). To this end, they receive a total of 32 worksheets with tasks and factual information on eight aspects. In the next step, all this information is assessed and visualized using green and red markings on the *AssessmentDisc* (Figure 2).

Figure 2. Extensive information material, assessed and marked on the AssessmentDisc (Banse & Marohn, 2021, 2022).



At the end, a conclusion can be drawn. The more green markings on the outer circle, the greater the controversy's impact on sustainability, because this means a *global*, *long-term* benefit for

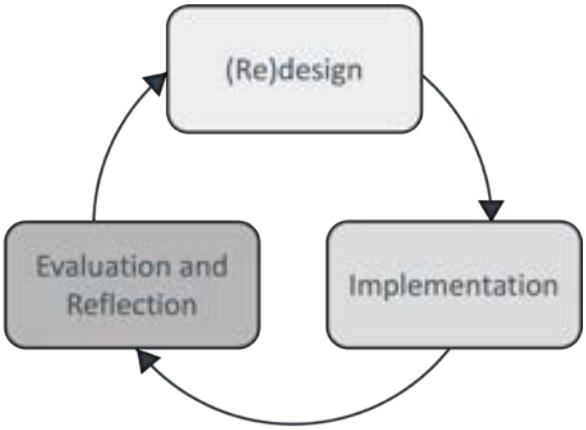
many groups.

Research Framework

Design-Based Research

The research uses the framework of design-based research (DBR) (Brown 1992; Collins, 1992) and follows the three phases of *Framing, Design Experiment* and *Re-Framing* (Gravemeijer & Cobb, 2006). In the *Design Experiment* phase there are iterative cycles (Figure 3) that include the development of a design (in this case: teaching approach *sustain.able?!*), its implementation and evaluation (Rohrbach-Lochner & Marohn, 2018). Each cycle is characterized by its own objectives and sub-research questions. The overarching goals of the DBR research process are to develop an innovative design for practical application (What works?) and to develop a theory about how the design works (How does it work?).

Figure 3. Iterative cycles in DBR (adapted from Rohrbach-Lochner & Marohn, 2018).



Research Gaps

A workshop with teachers ($N = 20$) showed that the teaching approach *nachhaltig.bewerten* still has some weaknesses (Banse, 2025). The majority of teachers criticized the high complexity and the large amount of information material that was provided to the students.

This resulted in students taking a long time to process the key points from the large amount of information material. Consequently, they only had little time left to assess the information. These areas for further research and additional ideas should be addressed in the approach *sustain.able?!*.

This paper focuses on just one of several research gaps and its solution.

Research Questions

Due to the research gaps described above, the presentation at ESERA focused on a stronger support for the assessment process. The following research questions were formulated:

RQ 1: How can the process of assessing information be made more structured and methodologically viable for students?

RQ 2: To what extent do students assess the information as intended?

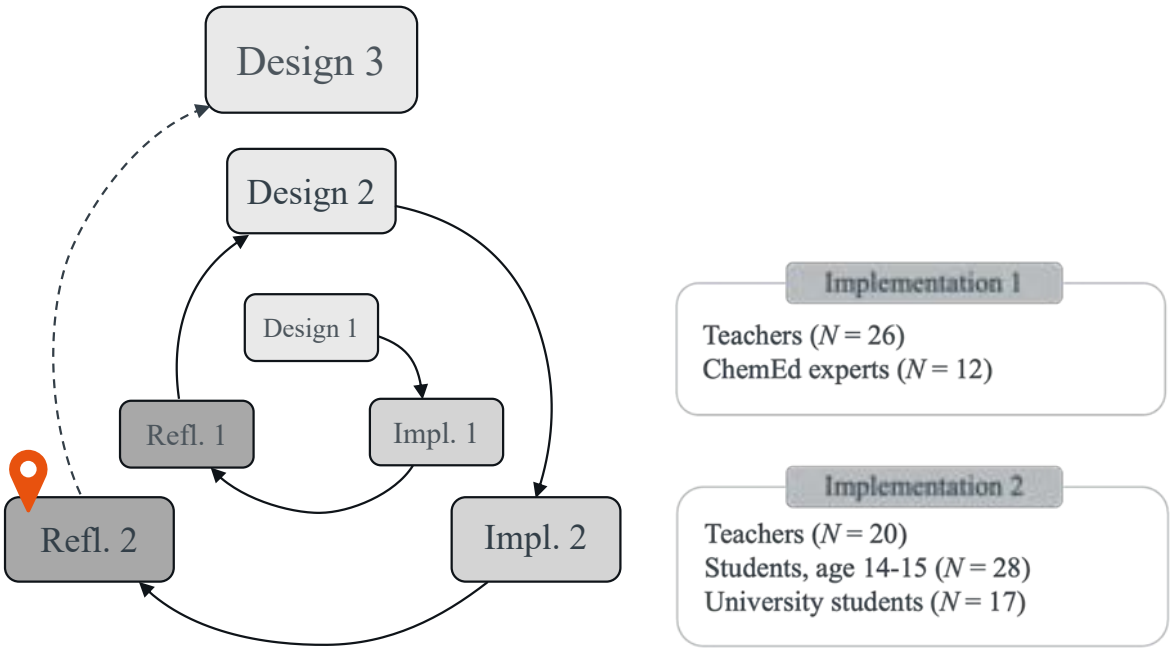
RQ 3: How do students evaluate the new methodological tool of '*AssessmentBubbles*'?

Method

The design (here: teaching approach *sustain.able?!*) for stronger support of the assessment process was tested, analysed and optimized in several trial cycles with students aged 14-15 ($N = 28$), teachers ($N = 46$), university students ($N = 17$) and experts in chemistry education ($N = 12$) (Figure 4). Data was collected via questionnaires for all samples. During the testing with

the students, pre-post-tests and audio and video recordings were also collected. This data was evaluated using qualitative content analysis (Kuckartz & Rädiker, 2024).

Figure 4. Iterative development of teaching materials within the sustain.able?! project.



Results

The Methodological Tool Of 'Assessmentbubbles' (RQ 1)

The *AssessmentBubbles* (Figure 5) were developed as direct outcomes of research question 1 to provide greater support for the assessment process for students. Compared to the previous approach, the assessment is supported by three measures:

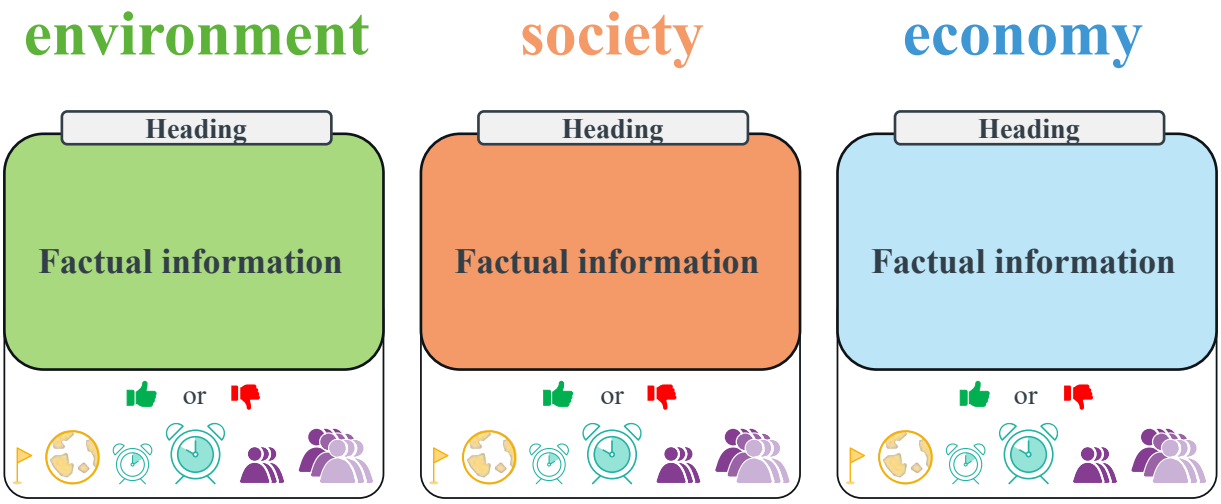
a) Students receive much more compressed factual information. They do not have to work through numerous worksheets to gather the information themselves.

b) The information is assessed directly in the immediate proximity of the information. In addition to scientifically based information, an *AssessmentBubble* also contains an assessment section. The assessment of the information takes place in two steps. First, students decide whether the information describes a benefit or harm and circle the corresponding symbol (green or red thumb). Afterwards, they assess the *AssessmentLevels*, considering the space (*local* or *global*), the timeframe (*short-term* or *long-term*) and affected groups (*one group* or *many groups*) for demonstrated benefits or harms. They mark the corresponding symbols of the *AssessmentLevels* from Banse & Marohn (2021, 2022).

c) The colour of the *AssessmentBubble* directly indicates the dimension to which the information refers*: environment* (green), *society* (orange) or *economy* (blue).

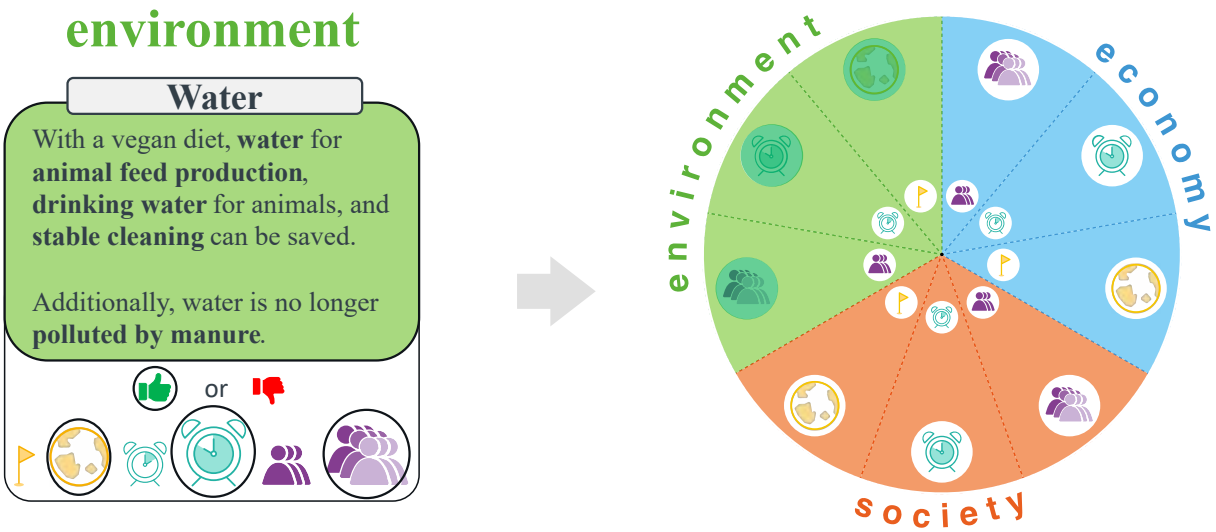
In the next step, the assessments from the bubbles are transferred to the *AssessmentDisc*. This can be illustrated with the example of *vegan diets,* where the sustainability of a plant-based diet is compared to one that includes animal products. This context was chosen because of its relevance to the students' lives, the breadth of available information and its alignment with the German biology curriculum.

Figure 5. AssessmentBubbles in the project sustain.able?!.



The ‘water’ aspect describes the lower water consumption and avoidance of water pollution caused by manure in the case of a *vegan diet*, representing a *global*, *long-term* benefit for *many groups*. Accordingly, the symbols are circled on the *AssessmentBubble* and transferred to the *AssessmentDisc* with green markings (benefit) within the *environment* dimension (Figure 6).

Figure 6. Transfer from the AssessmentBubble to the AssessmentDisc.

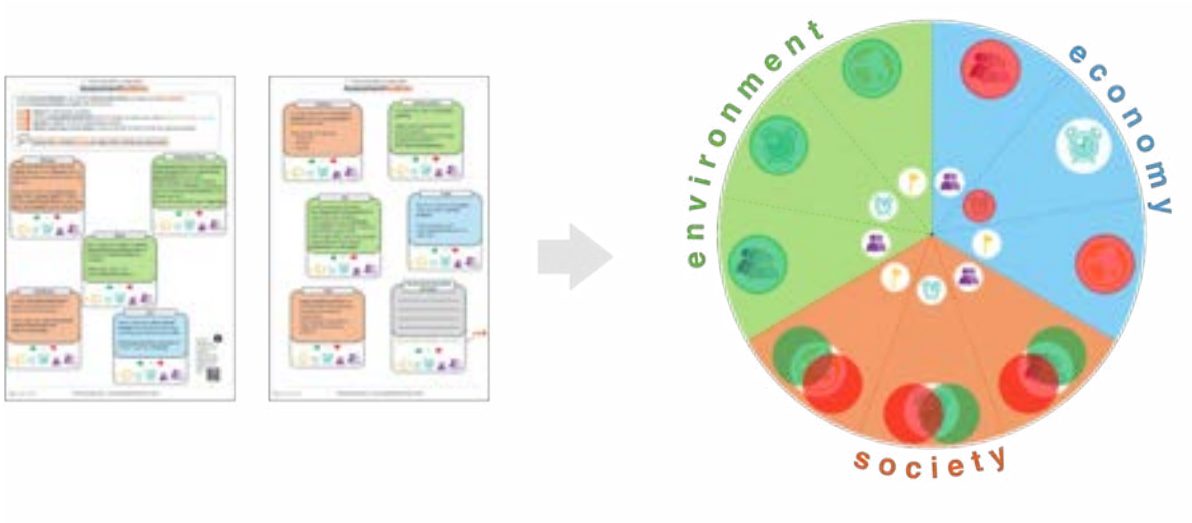


In a sustainability controversy students receive several *AssessmentBubbles* containing information from all three dimensions. The *AssessmentBubbles* are all included on only two worksheets (Figure 7). Once all *AssessmentBubbles* have been transferred to the *AssessmentDisc*, a differentiated picture of the sustainability of the controversy under consideration emerges (Figure 7).

Assessment Of The Information In The Assessmentbubbles (RQ 2)

To draw conclusions about the understanding of the new method *AssessmentBubbles*, the information in the bubbles assessed by the learners ($N = 28$) were analysed. Each student assessed 10 information (in 10 bubbles), so a total of 280 bubbles were evaluated.

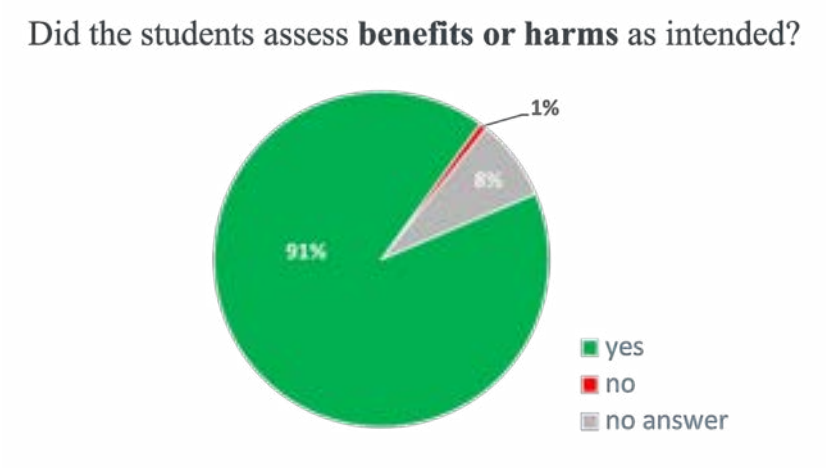
Figure 7. Example 'vegan diet', AssessmentBubbles and AssessmentDisc.



Benefits And Harms

Examining the results of the first step, in which students classified the information in the bubbles as a benefit or a harm, reveals a high accuracy: Over 90 % of the bubbles were classified correctly (Figure 8).

Figure 8. Assessment of benefits and harms by students.



AssessmentLevels

For each *AssessmentBubble* the three *AssessmentLevels* (*Where? How long? Who?*) are considered in addition to the benefits and harms. Therefore, an analysis was conducted to determine how many of the intended levels were assessed per bubble – one, two, or all three. In more than 80 % of the bubbles at least 2 out of 3 *AssessmentLevels* were correctly assessed (Figure 9).

Feedback On The Tool 'Assessmentbubbles' (RQ 3)

After the trial the students provided feedback on the method *AssessmentBubbles* via a five-point Likert scale questionnaire containing the following items, translated from German:

1 It was easy for me to assess whether the information described a *benefit* or a *harm.*

2 It was easy for me to assess *where*, for *how long*, and for *whom* the benefit or harm is shown.

3 It was easy for me to transfer from the Bubbles onto the *AssessmentDisc*.

4 The *AssessmentBubbles* gave me a good overview of the topic of *vegan die*t.

The results show predominantly positive feedback (Figure 10).

Figure 9. Assessment of AssessmentLevels by students.

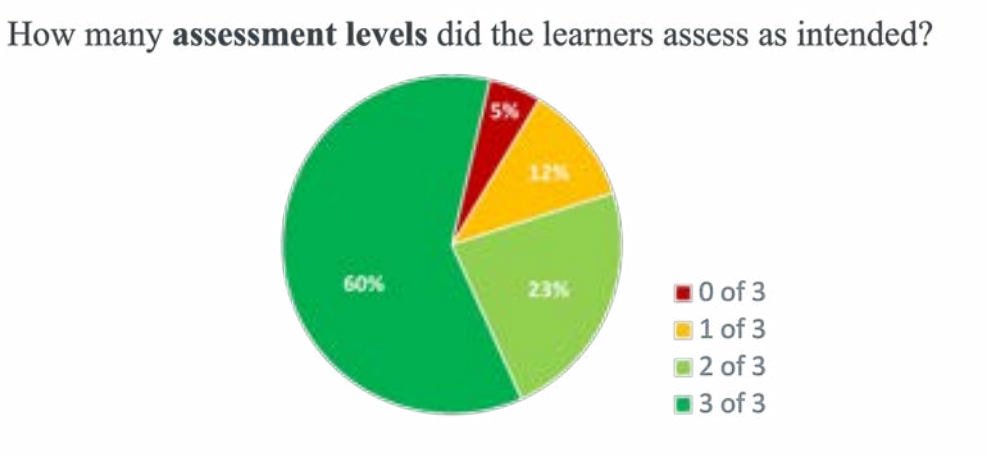
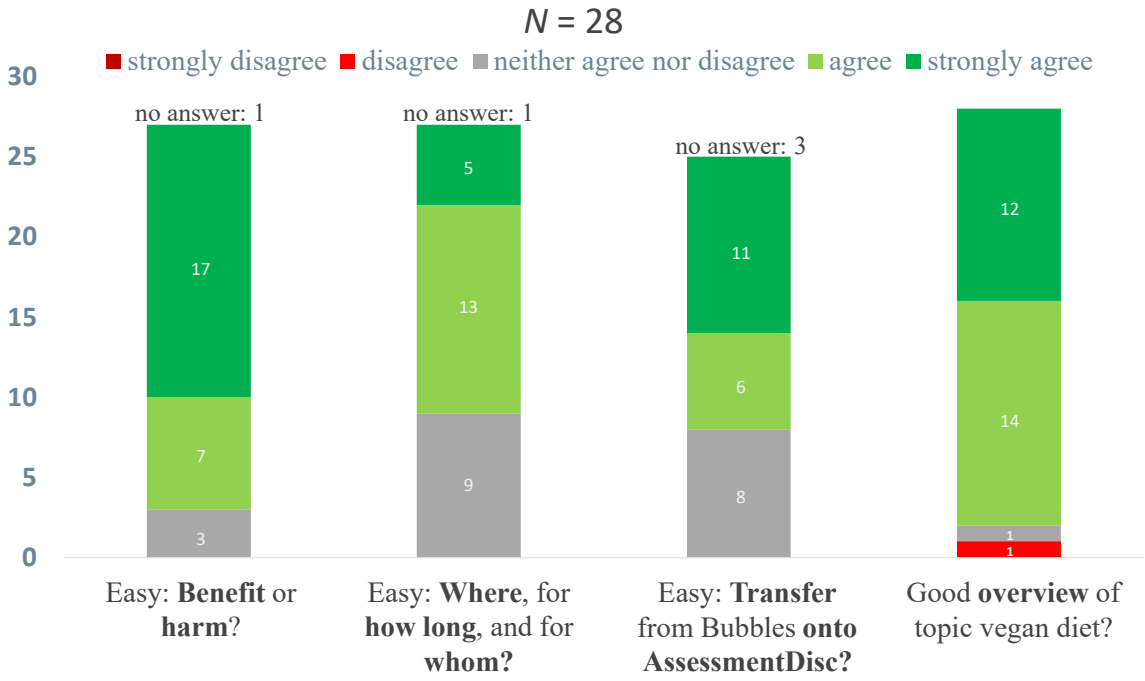


Figure 10. Assessment of AssessmentLevels by students.



The evaluations of the initial results indicate that *AssessmentBubbles* can support the assessment process for learners.

Summary And Outlook

The *sustain.able?!* teaching approach as a further development of the *nachhaltig.bewerten* approach aims to enable learners to assess the sustainability of a controversy in a criteria-based manner considering the three dimensions of *environment*, *economy* and *society*. Both approaches leverage *AssessmentLevels* (space, time, group) and the *AssessmentDisc* to guide this process.

The new methodological tool *AssessmentBubbles* in the teaching approach *sustain.able?!* has succeeded in simplifying and supporting the process of assessing information through a) compressed information, b) the immediate proximity of information and assessment and c) the color-coding of information according to sustainability dimensions.

Initial trials with students aged 14-15 demonstrate that the *AssessmentBubbles* effectively support learners in assessing sustainability controversies.

Expanding the approach to other scientific topics, increasing support for implementation in the classroom (e.g., developing a free app), and encouraging deeper reflection among students on sustainable decisions will be the next steps in this research project.

Furthermore, in line with the iterative process in DBR, Design 3 (Figure 4) is developed following an in-depth analysis of the data from the trial with the students. These revised teaching materials will then be tested with a larger sample of students.

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ESERA 2025 Copenhagen

How To Teach In Times Of Biodiversity Loss: Pedagogical Approaches To Transform Our Relationship With Nature

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Pontificia Universidad Católica de Valparaíso, Chile

Biodiversity loss, exacerbated by climate change, represents a critical challenge that demands an integrated educational response. This article presents a narrative review exploring pedagogical approaches aimed at improving students' attitudes towards biodiversity and fostering pro-environmental behaviours. Recent literature identifies four main educational challenges: promoting positive attitudes towards biodiversity, increasing environmental literacy, fostering environmental efficacy, and reducing maladaptation due to climate anxiety. In response, three key pedagogical approaches are proposed: place-based education (PBL), Field Environmental Philosophy (FILAC), and the development of personalized ecologies. These strategies, including field trips, nature journaling, and the creation of gardens and green spaces, are highlighted for their ability to connect students with nature while fostering socioemotional and critical thinking skills. However, their implementation faces barriers such as limited time, resources, and adequate teacher training. It is concluded that integrating these approaches into school curricula can help build a citizenship committed to sustainability and environmental regeneration, especially if supported by teacher professional development programs that enhance their application across diverse educational contexts.

Keywords: Environmental education, biodiversity loss, place-based pedagogy

Introduction

Human-driven alterations to ecosystems are producing profound and cascading effects that compromise their functioning, stability, and resilience. Processes such as forest fragmentation, agricultural intensification, and the widespread use of pesticides disrupt species richness, trophic networks, nutrient cycling, pollination, and pest regulation, generating long-term consequences for ecosystem integrity (Haddad et al., 2015; Sánchez-Bayo & Wyckhuys, 2019; Dirzo et al., 2014). These pressures are expected to intensify under climate change, which further alters population dynamics, ecological interactions, habitat connectivity, and ecosystem resilience (IPBES, 2019).

Despite the magnitude of biodiversity loss, its consequences are often difficult to perceive and evaluate. Individuals, including scientists, tend to assess environmental change relative to the conditions they first experienced, a cognitive bias known as the shifting baseline syndrome, whereby progressively degraded states become normalised across generations (Soga & Gaston, 2018). This phenomenon is closely linked to the extinction of experience, referring to the gradual decline in meaningful human–nature interactions, which in turn shapes environmental attitudes and behaviours (Gaston & Soga, 2020; Colléony et al., 2020).

Understanding how people relate emotionally and cognitively to the natural world is therefore central to biodiversity conservation. Concepts such as biophilia—the affective affinity toward other living beings—and biophobia—negative emotions and attitudes toward nature—capture the emotional dimensions of human–nature relationships, both of which are strongly shaped by cultural, social, and educational contexts (Woods & Knuth, 2023; Albuquerque & Silva, 2024; Soga & Evans, 2024). While biophilic relationships are associated with greater willingness to engage in conservation actions, biophobic responses can reduce support for biodiversity protection and even promote species persecution (Soga et al., 2023). Consequently, fostering positive, experience-based relationships with nature through education has been identified as a

key strategy for counteracting biophobia and promoting conservation-oriented behaviours (Deutsch et al., 2021; Zsido et al., 2022).

However, strengthening connections with nature is not without tension. Greater environmental awareness and emotional identification with nature have also been linked to increased psychological distress, as individuals perceive climate change and biodiversity loss as threats to their own well-being and future (Curll et al., 2022; Wullenkord et al., 2024). These responses have been conceptualised as climate anxiety and eco-anxiety, which, while not pathological in themselves, may exacerbate mental health challenges and lead to maladaptive coping strategies if left unaddressed (Crandon et al., 2024). Educational approaches that seek to promote environmental engagement must therefore balance ecological awareness with emotional support and resilience.

In response to the intertwined ecological and emotional dimensions of the biodiversity crisis, educational systems are increasingly called upon to move beyond purely cognitive or technocratic models. This shift involves reimagining education as a space for cultivating ecological justice, relational understandings of humans as ecological beings, and forms of coexistence with the more-than-human world (Common Worlds Research Collective, 2020). Yet, implementing such transformations presents significant challenges for teachers, who must navigate not only curricular demands but also their own emotional responses—and those of their students—to the climate and biodiversity crises (Suarez et al., 2024). Within this context, science education emerges as a critical arena for integrating ecological knowledge, emotional engagement, and ethical responsibility in ways that support both biodiversity conservation and human well-being.

Aims Of Study

The study aims to:

1. Synthesize evidence on the formation of environmental attitudes and behaviours.
2. Synthesize the evidence on pedagogical approaches that promote positive relationships with biodiversity.
3. Propose evidence-based guidelines for designing impactful science education practices.

Methods

A literature review was conducted using Scopus, focusing on:

- Biodiversity, well-being, and human development.
- Educational strategies addressing biodiversity loss and emotional well-being.
- The intersection of environmental education and socio-emotional development.

Inclusion criteria emphasized recent (post-2014) empirical and theoretical studies relevant to primary and secondary education. Exclusions included higher education contexts, non-educational interventions, and studies addressing aspects of the climate crisis such as greenhouse gas emissions, pollution, or carbon footprints, without directly considering biodiversity. Emerging themes guided additional searches to refine the conceptual and practical recommendations.

The complete list of search terms included combinations such as:

- Biodiversity AND Wellbeing
- Environmental literacy
- Environmental literacy AND Teachers

- Climate change AND Education
- Wellbeing AND Environmental education
- Environmental education AND Chile
- Biophilia AND Education
- Biophobia AND Education

The findings of the review were synthesized and organized in alignment with the study aims. First, evidence was examined to identify key processes involved in the formation of environmental attitudes and behaviours. Second, the literature was analysed to characterize pedagogical approaches and educational strategies that promote positive relationships with biodiversity. Finally, insights from both strands of evidence were integrated to inform the development of evidence-based guidelines for the design of impactful science education practices that intentionally address both cognitive and affective dimensions of human–biodiversity relationships.

Results

The results are organized into four sections that collectively address the three aims of the study. The first two sections synthesize evidence on the formation of environmental attitudes and behaviours, responding to the first aim. Specifically, the section on *Relationships with Nature* examines theoretical and empirical contributions that explain how affective, experiential, and cognitive dimensions—such as personalised ecologies, biophilia, and species knowledge—shape human–biodiversity relationships. The section on *Climate anxiety and eco-anxiety* complements this perspective by focusing on emerging emotional responses to environmental degradation, highlighting how these emotions can both motivate and constrain pro-environmental action depending on factors such as environmental efficacy and emotional competencies.

The third section addresses the second aim by reviewing educational strategies that intentionally foster positive relationships with biodiversity in school contexts through locally grounded, experiential, and affectively rich approaches. Finally, the fourth section responds to the third aim by synthesizing evidence from the previous sections to identify key educational challenges and propose evidence-based guidelines for designing science education practices that intentionally integrate attitudinal, emotional, and action-oriented dimensions of environmental learning.

Relationships With Nature

Personalised ecologies have emerged as a useful framework for examining how individuals relate to nature through direct, sensory interactions with other species and their ecosystems (Gaston et al., 2018). These ecologies are shaped by the dynamic interplay of external and internal factors, including opportunities to engage with nature, individual capacities to participate meaningfully in such interactions, and the motivations guiding behaviour toward natural environments (Gaston, 2024). Evidence suggests that rich and diverse personalised ecologies are associated with more positive attitudes toward biodiversity and a greater willingness to engage in conservation actions, whereas impoverished or predominantly negative experiences with nature are linked to increased biophobia (Gaston et al., 2023).

This perspective aligns with broader research on the development of human–nature relationships, which highlights the importance of formative experiences during childhood. In particular, exposure to influential social models and engagement in meaningful nature-based activities, such as observing natural processes or cultivating plants, have been identified as strong predictors of higher levels of nature connectedness in adulthood (Gong & Li, 2024). Furthermore, perceived

knowledge of local species has been shown to reduce emotions associated with biophobia, including fear, disgust, and misperceptions of danger (Soga et al., 2020). In educational contexts, strategies aimed at enriching personalised ecologies, such as fostering species identification skills, providing regular opportunities for interaction with natural elements, and facilitating contact with experts in natural history and conservation, may therefore play a key role in promoting biophilia, ecological literacy, and pro-environmental behaviours.

Climate Anxiety And Eco-Anxiety

Growing evidence indicates that younger people, particularly those belonging to Generation Z, experience climate and eco-anxiety with greater intensity and emotional awareness in response to the global climate crisis (Tsevreni et al., 2023; Wullenkord et al., 2024). These heightened emotional responses are not uniformly maladaptive; when accompanied by a strong sense of environmental efficacy—the belief that individual and collective actions can meaningfully contribute to climate mitigation—climate anxiety has been shown to motivate pro-environmental behaviours (Becht et al., 2024). However, research also suggests that differences in emotional education shape how individuals cope with these emotions, with gendered patterns emerging in which men tend to report fewer emotional resources for managing climate-related anxiety (Wullenkord et al., 2024). Taken together, these findings underscore the importance of educational approaches that integrate emotional competencies to reduce distress while supporting constructive engagement with environmental challenges.

Educational Strategies

Place-based education (PBE) has emerged as a pedagogical approach aimed at addressing environmental challenges by situating learning within local communities and their socio-environmental issues, thereby integrating formal education, environmental stewardship, and community development (Smith, 2017). Drawing on multiple educational traditions, PBE employs strategies such as project-based learning, field trips, scientific camps, and nature journaling to connect disciplinary knowledge with students' lived environments (Bollich, 2023; Yemini, Engel, & Ben Simon, 2023). Empirical evidence suggests that this approach enhances learning outcomes, particularly when students perceive opportunities to make decisions about their learning processes and recognize that their work contributes meaningfully to environmental protection or restoration. Nevertheless, its implementation is often constrained by limited instructional time, insufficient funding, and gaps in teacher preparation (Hamilton & Marckini-Polk, 2023).

Complementary to this approach, playscapes—designed environments that recreate local natural landscapes under controlled conditions—seek to promote exploration, sensory engagement, and diverse forms of play (Carr & Luken, 2014). The variation in topography and the availability of both natural and artificial movable elements support predominantly exploratory and physical play, while also enabling social interaction and self-care activities (Loebach & Cox, 2022). Research indicates that learning and play within playscapes foster intrinsically motivated forms of inquiry, encourage environmentally responsible behaviours, and stimulate creativity and goal flexibility, all of which contribute to a stronger emotional bond with the environment by promoting feelings of safety and agency (Wight et al., 2016; Yuan et al., 2024).

In the Chilean context, related initiatives provide further evidence of the educational potential of locally grounded, nature-based approaches. The implementation of Life Labs—student-managed school gardens integrating emotional skills, empathy, and critical thinking—has been associated with increased pro-environmental behaviours, the development of dispositions such as open-mindedness, self-confidence, and truth-seeking, and a reduction in disruptive behaviours,

particularly among younger students (Ampuero et al., 2015). Similarly, Field Environmental Philosophy (FILAC) combines ecological and philosophical knowledge to design ethically and ecologically oriented educational experiences, including contemplative practices, drawing as a tool for observation and interpretation, sensory exploration, creative engagement with local species, and the development of school-based scientific projects linked to fieldwork (Rozzi, 2018; Lewis et al., 2018; Rendoll-Cárcamo et al., 2020).

Educational Guidelines To Promote Positive Attitudes And Relationships Toward Biodiversity

Based on the reviewed literature on the formation of attitudes and relationships with nature, as well as the challenges that biodiversity loss poses for society in general and the educational system in particular, the reviewed literature indicates that education faces the following challenges:

1. Enriching personalized ecologies by fostering biophilia and mitigating biophobia, understanding them as positive and negative emotions and attitudes toward biodiversity and living beings, respectively.
2. Increasing environmental literacy and, therefore, individuals' capacity to recognize both the different components of biodiversity and the potential threats it faces.
3. Promoting environmental efficacy, that is, the belief that individual and collective actions have a significant impact on mitigating climate change.
4. Reducing the likelihood of maladaptation due to climate anxiety and eco-anxiety through emotional management skills.

Based on the reviewed evidence, we propose that education aimed at promoting positive attitudes and relationships toward biodiversity should follow three guidelines to guide educational practices:

1. Create opportunities for meaningful interaction with nature, both inside and outside the classroom.
2. Promote positive impacts on the immediate local environment through projects that connect students with their context.
3. Develop emotional and critical thinking skills that enable students to face environmental and emotional challenges.

Discussion

Accelerated biodiversity loss, intensified by climate change, poses complex challenges that require educational responses aimed at fostering environmentally respectful societies. Within this context, incorporating the concept of personalised ecologies into education involves recognising that individuals' interactions with the natural environment vary across social groups and life experiences, and that these interactions are fundamental for building meaningful relationships with nature. Enriching students' personalised ecologies aligns with the objectives of Natural Sciences education, which seeks not only to develop scientific knowledge about biodiversity but also to cultivate curiosity, wonder, and engagement with the natural world (MINEDUC, 2024).

The literature indicates that rich and diverse personalised ecologies are associated with higher levels of environmental literacy, stronger pro-environmental behaviours, and a reduced susceptibility to shifting baseline syndrome, which limits individuals' capacity to perceive environmental degradation over time (Gaston et al., 2023). This evidence supports the integration of approaches such as place-based education (PBE) and Field Environmental Philosophy

(FILAC), both of which promote sustained, direct engagement with local environments and thus contribute to the development of enriched personalised ecologies. In Chile, environmental education teachers have emphasised the need to incorporate outdoor learning spaces and practical, collaborative approaches that actively involve local communities, reinforcing the relevance of these pedagogical frameworks (Prosser-Bravo et al., 2022).

Flexible strategies such as field trips and nature journaling further support these aims, as they can be adapted to diverse curricular contexts, contents, and time constraints. Nature journals, in particular, may function either as components of inquiry-based projects or as pedagogical activities in their own right, fostering students' connections with their environment, their peers, and themselves (Bollich, 2023; Lewis et al., 2018; Tsevreni, 2021). Through these practices, opportunities emerge not only to enrich personalised ecologies but also to strengthen positive emotions toward nature and develop socio-emotional competencies.

Despite their potential, the implementation of these approaches in the Chilean educational system faces persistent challenges, including limited time for planning and execution, restricted access to resources, uneven levels of institutional support, and variations in teachers' prior experience with environmental education (Prosser-Bravo et al., 2020). While PBE and FILAC can be integrated into the regular curriculum—particularly within subjects designed to apply scientific knowledge to interdisciplinary and socially relevant contexts—their effectiveness ultimately depends on sustained commitment from the broader school community.

Community engagement is also central to initiatives aimed at promoting biophilia through the creation of educational green spaces, such as gardens, orchards, playscapes, green roofs, and living walls. These environments have been shown to support the development of pro-environmental attitudes and socio-emotional skills; however, both the underlying biological processes and the associated attitudinal and emotional changes require time to emerge. Importantly, the skills and dispositions fostered in these settings align with Chile's Cross-cutting Learning Objectives and, in the current curricular framework, are increasingly integrated into subject-specific learning goals (MINEDUC, 2016, 2018, 2024). This alignment highlights the broader educational value of such practices, particularly in relation to emotional regulation and resilience, which are critical for mitigating the negative effects of climate and eco-anxiety.

Finally, teacher education and professional development represent key leverage points for the effective integration of these approaches. Research in Chile has documented that environmental education is frequently delivered by teachers without specialised scientific training, limiting the integration of cognitive, procedural, and affective dimensions of environmental learning (Torres-Rivera et al., 2017; Karelovic-Vargas & Kong, 2022). Moreover, these challenges extend beyond non-specialist teachers, as even educators with scientific backgrounds report insufficient preparation to address sustainability in educational contexts (Quiroz-Martínez, 2024). Consequently, embedding these pedagogical frameworks within both initial teacher education and ongoing professional development is essential. As prior studies suggest, successful environmental education requires not only exposure to natural settings but also pedagogical practices that intentionally foster affectivity, empathy, play, and interaction with both the environment and others (Bertling, 2019; Gong & Li, 2024).

Conclusion

Education is at a crucial moment to address environmental challenges, such as biodiversity loss and its effects on human well-being. This work identifies four key challenges: fostering positive relationships and emotions toward biodiversity, increasing environmental literacy, promoting environmental efficacy, and reducing eco-anxiety. Three guidelines are proposed to address these

challenges: creating meaningful interactions with nature, generating positive impacts on the environment, and developing emotional and critical thinking skills. Place-based education and Field Environmental Philosophy approaches, along with strategies such as field trips, nature journaling, and the creation of green spaces, are presented as effective tools. However, it is crucial to overcome obstacles such as lack of time, resources, and community support, as well as to have trained teachers, to achieve an education that shapes citizens committed to the conservation and regeneration of the environment.

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Cross-Cultural Analysis Of Stem Human Resources Community Influences On Gender: Focus On Higher Education Students In Japan, America, And Malawi

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In countries such as Japan, which strongly promotes science, technology, engineering, and math (STEM), human resource policies have increased. In education, the importance of a competency model is widespread; however, because many aspects of competency are influenced by the cultural background of individuals, certain considerations must be made for international comparisons. This study examines the culture of STEM and proposes a competency model for STEM human resources in a global context, particularly focusing on gender. For this, a 21-question survey was conducted among culturally diverse Higher education students (Japan, America and Malawi); 252 males and 157 females. There were significant differences between male and female students in the target country for 10 of the 21 ability elements. Significant gender differences were observed in STEM human resource consciousness and recognition, such as "collaboration," "ability to apply rules and regulations," and "ethics."

Keywords: Gender in STEM, Higher Education, STEM education

Introduction

In Japan, fostering science and technology-related human resources and innovation has become increasingly important in recent years. This is evident in the establishment of a Minister's Meeting task force at the Ministry of Education, Culture, Sports, Science and Technology (MEXT, 2018) based on the concept of "Society 5.0" (Cabinet Office, 2016). In this context, three abilities have been proposed: (1) ability to accurately interpret and respond to writing and information; (2) ability to engage in and apply scientific thinking and inquiry; and (3) sensitivity and ability to discover and create value, as well as curiosity and inquisitiveness, within a human resource profile.

However, because many aspects of competency are influenced by individuals' cultural backgrounds, certain considerations must be made when making international comparisons. This study focuses on the culture of science, technology, engineering, and math (STEM) and proposes a competency model for STEM human resources in a global context, particularly focusing on gender.

While previous studies, such as those by Kuroda (2021) and Kuroda (2022), have used Japan and Africa (Malawi) as case studies, Kuroda (2024) examined Japan and the America. This study focuses on gender and considers Japan, Malawi, and the America as case studies. America is an advanced country that has been actively promoting STEM education. In 2010 and 2012, the President's Council of Advisors on Science and Technology published reports to increase the number of people working in STEM fields (President's Council of Advisors on Science and Technology, 2010 / 2012). These policies have been in effect for over a decade. Malawi is one of the poorest countries worldwide, with a gross national income per capita of 600 US dollars (World Bank, 2023). For many years, the Japanese government has provided educational support for science and mathematics in Malawi as part of its official development assistance. Consequently, Malawi shares some characteristics of science and mathematics education with Japan, making it a suitable candidate for comparative analysis.

Therefore, the following research questions (RQs) were established to examine competencies

common to the global STEM workforce:

RQ1: What are the characteristics of the STEM human resources community among students in the target country, and do these perceptions differ by gender?

RQ2: How can RQ1 be clarified by examining common consciousness and recognition among students in the target country?

Methods

In this study, a survey was conducted among culturally diverse Japanese, American, and Malawian students. The Japanese students were first- year students in the Faculty of Science at a local national university. The survey was conducted at the end of Quarter 2, as the university operates based on a quarter system). In this faculty, students can major in mathematics, physics, chemistry, biology, and geography, with approximately 36% advancing to graduate schools. The American students were recruited from freshman biology classes at a large midwestern university, while the Malawian students were first- and second-year students at an ICT vocational school, and a survey was conducted at the end of the year.

A total of 228 Japanese (male: 172, female: 56), 116 Americans (male: 44, female: 72), and 82 Malawian (male: 36, female: 29, not answered: 17) students participated in the study. Overall, the number of males and females was 252 and 157, respectively. This study extends previous research by Kuroda (2021, 2022, 2024), and other studies, utilizing the ability elements in the survey. The questionnaire consisted of 21 items based on the Fundamental Competencies for Working Persons, published by various Japanese government departments (1; Expertise (general), 2; Leadership, 3; Management, 4; Information, Media, and Technology Literacy, 5; Initiative, 6; Ability to Influence Others, 7; Executing Plans, 8; Ability to Detect Issues, 9; Creativity, 10; Critical Thinking, 11; Collaboration, 12; Communication, 13; Innovation, 14; Ability to Deliver Messages, 15; Ability to Listen Closely and Carefully, 16; Flexibility, 17; Ability to Grasp Situations, 18; Ability to Apply Rules and Regulations, 19; Ability to Control Stress, 20; Ethics, 21; Career Development and Planning).

The questions included: “How important are these skills and abilities for people with STEM careers?” Responses were recorded on a 5-point Likert scale, where 5 indicated “very important,” 4 “important,” 3 “somewhat important,” 2 “not very important,” and 1 “not at all important.” Average values were calculated based on the responses.

Results And Discussion

The survey results are summarized in Figure1 and Figure2. The options with more than 80% positive responses (responses to Options 4 and 5) were 13 for males (1, 2, 4, 5, 6, 7, 8, 9, 10, 12, 15, 16, and 17) and 19 for females (excluding 3 and 19). This indicates that the women exhibited a particularly strong awareness of the importance of the abilities assessed in the survey.

To confirm the difference in awareness more strongly, a *t*-test was conducted, revealing a significant difference in 10 items (Table 1). By contrast, Kuroda (2021), who focused on students in Japan and Malawi, found five items with significant differences. Thus, by expanding the target country, there is a possibility of a greater gender difference. In particular, the items “collaboration,” “ability to apply rules and regulations,” and “ethics” exhibited differences of more than 0.3 points in the responses, indicating a possibility of a greater gender-based influence.

Additionally, 11 items showed significant differences, and these items could be considered common factors for STEM human resources who can actively contribute to the STEM human resources community. However, the degree of positive response for “Management” and “Ability to Control Stress” was only approximately 70%. Therefore, the degree of positive response should

also be considered an element that must be examined.

Figure 1. Results of importance perceptions (Male)

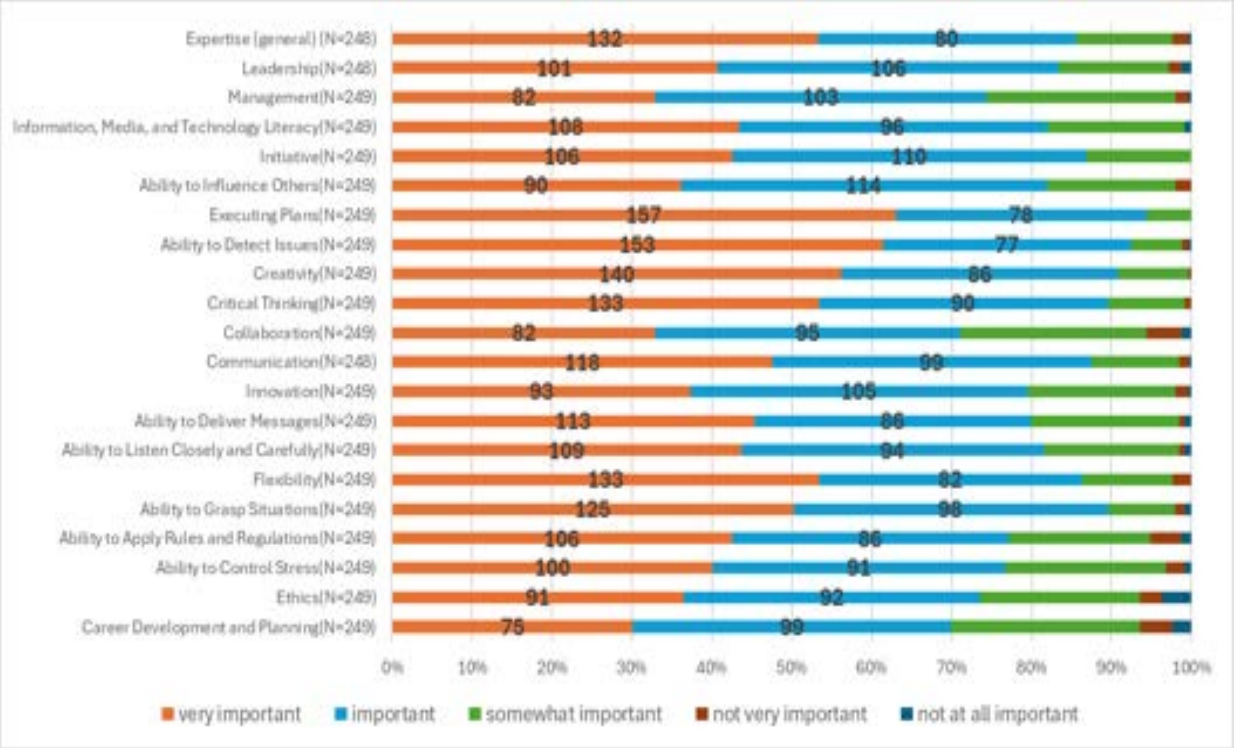
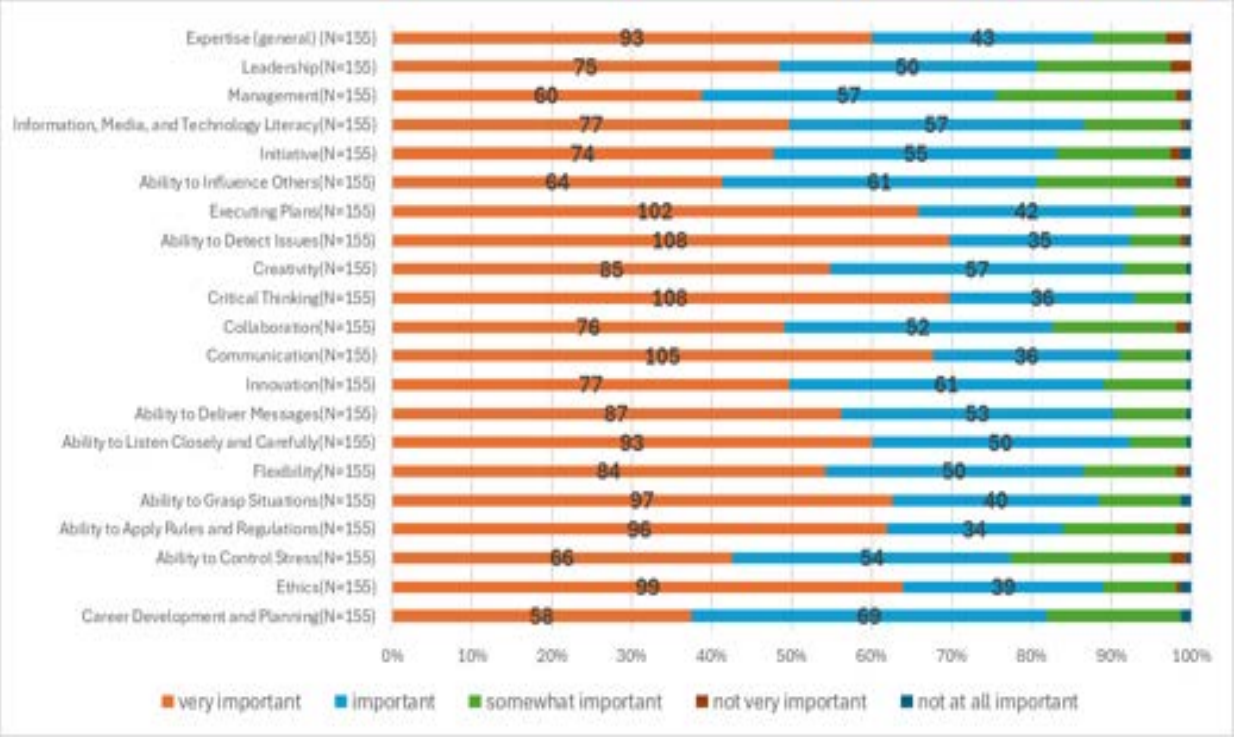


Figure 2. Results of importance perceptions (Female)



Conclusion

This study focuses on abilities within the STEM human resource community. Significant differences were found between male and female students in the target country for 10 of the 21 ability elements. Significant gender differences were observed in STEM human resource consciousness and recognition factors such as “collaboration,” “ability to apply rules and regulations,” and “ethics.”

Table 1. STEM human resources community ability *t*-test

	Male Mean(SD)		Female Mean(SD)	*t*	df
Expertise (general)	4.36(0.802)		4.44(0.815)	-0.963	323.3
Leadership	4.20(0.825)		4.26(0.830)	-0.742	325.3
Management	4.05(0.817)		4.12(0.845)	-0.796	318.4
Information, Media, and Technology Literacy	4.24(0.791)		4.34(0.768)	-1.32	333.9
Initiative	4.29(0.689)		4.27(0.848)	0.288	402.0
Ability to Influence Others	4.16(0.761)		4.19(0.815)	-0.405	309.9
Executing Plans	4.57(0.599)		4.57(0.693)	0.0973	291.1
Ability to Detect Issues	4.52(0.690)		4.60(0.699)	-1.09	323.7
Creativity	4.47(0.672)		4.45(0.695)	0.203	318.4
Critical Thinking **	4.42(0.698)	<	4.61(0.668)	-2.72	402.0
Collaboration **	3.97(0.922)	<	4.29(0.822)	-3.61	354.7
Communication **	4.33(0.750)	<	4.57(0.702)	-3.30	343.1
Innovation **	4.14(0.800)	<	4.37(0.722)	-2.98	351.8
Ability to Deliver Messages **	4.23(0.833)	<	4.45(0.713)	-2.76	402.0
Ability to Listen Closely and Carefully **	4.23(0.813)	<	4.51(0.687)	-3.58	402.0
Flexibility	4.37(0.778)		4.38(0.792)	-0.0889	322.6
Ability to Grasp Situations *	4.37(0.757)	<	4.48(0.784)	-1.44	317.9
Ability to Apply Rules and Regulations **	4.13(0.926)	<	4.43(0.830)	-3.38	353.4
Ability to Control Stress	4.13(0.870)		4.17(0.859)	-0.444	330.0
Ethics **	4.00(1.00)	<	4.50(0.793)	-5.52	379.9
Career Development and Planning **	3.92(0.955)	<	4.17(0.796)	-2.79	402.0

※ * : p <.05 ** : p <.001

However, this study has certain limitations. First, it considers data from only three countries, and second, it only considers freshman-level students. Therefore, it is necessary to collect data from different countries and grade levels. Future studies should gather information from other countries and conduct further interviews with survey respondents.

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ESERA 2025 Copenhagen

In Science We Trust? Examining Institutional Trust, Information Sources, and Climate Literacy Among Future Teachers

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Climate literacy is vital for future educators, the key facilitators of public understanding of climate change. This study examines how climate literacy, knowledge sources, and trust in scientific institutions interact to influence pre-service teachers' climate understanding. A survey of Greek University students assessed their climate knowledge, sources of information, environmental education, and trust in scientific institutions. Results indicate that formal education enhances reliance on structured sources, while digital platforms increase misinformation risks. A Climate Literacy Index (CLI) was developed, revealing that trust in scientific institutions strongly predicts climate literacy, while social media use correlates with climate misconceptions.

Keywords: climate literacy, teacher education, information sources

Introduction

Climate literacy is widely recognized as essential for informed decision-making and pro-environmental behaviour. For educators, and pre-service teachers in particular, climate literacy is of added importance, since they are actors of shaping public understanding of climate change. The challenge is that climate literacy extends beyond factual climate knowledge; it involves understanding climate systems, human–environment interactions, and the capacity to make evidence-based decisions (McCright et al., 2013). Accordingly, contemporary frameworks conceptualize climate literacy as a multidimensional construct that combines core climate science knowledge of the climate system, its causes, impacts, and response options (Leve et al., 2023; Aeschbach et al., 2025) with information skills related to accessing, evaluating, and communicating scientifically credible climate information (Shwom et al., 2017; Lubej et al., 2025). It further incorporates values, attitudes, and agency, including concern, responsibility, and willingness to engage in mitigation, adaptation, and public-sphere action (Choi et al., 2021; Kranz et al., 2022; Kolenatý et al., 2022), alongside a systems-oriented social-science perspective that accounts for human behaviour, social drivers, justice, and political dimensions shaping climate action (Shwom et al., 2017; Beach, 2023; Kranz et al., 2022).

Climate Literacy Components

Prior research indicates that information sources of high quality and credibility are essential to the "understanding" element of climate literacy (Dong et al., 2018). Traditional sources such as formal schooling, books, and government services have been associated with higher climate literacy scores (Höttecke & Allchin, 2020). Conversely, reliance on digital platforms, particularly social media, has been linked to greater exposure to misinformation and misconceptions about climate science (Lewandowsky et al., 2017). Therefore, integration of environmental education in academic curricula can reinforce the "decision-making" element of climate literacy as well, by enhancing learners' ability to critically evaluate information and by increasing reliance on structured sources over unverified online content (Clayton et al., 2015).

Table 1. Key components of climate literacy for educators

Component	Examples for (pre-service) teachers
Content knowledge	Greenhouse effect, drivers, impacts, solutions (Leve et al., 2023; Aeschbach et al., 2025)
Critical evaluation	Judging source credibility, evidence, statistics (Shwom et al., 2017; Ranney & Clark, 2016)
Communication	Explaining mechanisms, discussing tradeoffs (Shwom et al., 2017)
Normative/political literacy	Policy tools, justice, public vs private action (Kranz et al., 2022; Pan et al., 2023; Lestari et al., 2024)

However, climate literacy is not shaped only within academic settings. Outside formal education, individuals with greater trust in scientists, meteorological agencies, and environmental organizations demonstrate higher levels of climate literacy (van der Linden et al., 2017) and are less susceptible to climate-related misinformation (Feldman et al., 2011). Large international surveys show that scientific literacy and trust in science jointly predict climate change understanding and threat perception, with trust partially mediating the effect of literacy on understanding (Van Vleet & Fuller, 2024; Larrain et al., 2024; Pan et al., 2023).

In this study we examine how climate literacy, knowledge sources, and trust in scientific institutions interact to shape pre-service teachers' understanding of climate change.

Methodology

The study focuses on the following research questions:

RQ1: What are the primary sources of climate change knowledge for pre-service teachers, and how does having formal environmental education influence their reliance on these sources?

RQ2: How do different sources of climate information, formal education experiences, and demographic factors correlate with climate literacy (knowledge and behaviour), as measured by an integrated Climate Literacy Index?

RQ3: To what extent does trust in scientific institutions influence climate literacy among pre-service teachers, as measured by an integrated Climate Literacy Index?

Participants & Demographics

The sample consisted of 307 pre-service teachers enrolled in the 5th semester Geography course at a Greek University. Participants were 72% female, 27% male, and 1% identifying as non-binary or other. Their age ranged from 18 to 30 years old, with the majority (65%) falling within the 18-24 age range. Most participants were in their third year of study, and a small subset reported having prior degrees or higher education beyond the current program (this was captured as "higher education level" in our analysis). Participants' political orientation was assessed on a scale (ranging from more conservative to more liberal), given the potential influence of ideology on climate perceptions. Socioeconomic background information such as approximate household income and parental education was also collected for context. Participation in the study was voluntary and anonymous.

Data Collection

Data was collected through an online questionnaire administered during a scheduled laboratory session of the teacher education course. Participants received a survey link and completed the questionnaire on their personal devices under the supervision of the researchers. The survey took

approximately 20 minutes to complete. To encourage honest responses, participants were assured that their individual answers would remain confidential and would not affect their course standing. The questionnaire comprised several sections measuring climate literacy and its potential determinants, as described below.

Climate Literacy Measures

Climate literacy was assessed using a combination of knowledge-based items and behaviour/self-efficacy measures, reflecting its widely recognized multidimensional character encompassing knowledge, attitudes, and behaviours. Rather than adopting an existing single instrument, we developed a **Climate Literacy Index (CLI)** specifically for this study. This decision was informed by evidence that many available climate literacy measures are either predominantly knowledge-focused or designed for specific age groups, countries, or educational contexts, which limits their transferability to pre-service teacher populations (Leve et al., 2023; Lubej et al., 2025; Sato & Park, 2024). In addition, existing tools often insufficiently capture behavioural intentions, self-efficacy, and action readiness, dimensions increasingly considered central to climate literacy in education research (Kolenatý et al., 2022; Aeschbach et al., 2025). Developing a context-specific composite index therefore allowed us to integrate climate science understanding with behavioural and self-efficacy components relevant to the professional role and common misconceptions of future teachers, in line with contemporary calls for multidimensional and population-sensitive climate literacy assessments (Matlack et al., 2023; Nayan et al., 2020).

The knowledge component of the CLI comprised 15 multiple-choice and true/false items assessing core climate change concepts, including causes, evidence, impacts, and scientific consensus. Several items targeted well-documented misconceptions, such as confusing ozone depletion with climate change or perceiving impacts as exclusively future-oriented. Item development was informed by climate literacy frameworks and prior research on public misconceptions, and content validity was ensured through expert review by two climate science educators. Correct responses were summed to yield an individual knowledge score (range 0–15).

The behavioural component included 16 Likert-type items measuring self-reported climate-relevant behaviours and intentions related to mitigation and adaptation, such as energy conservation, sustainable transport, waste reduction, civic engagement, and climate-related discussions. Behaviours were included to capture the action-oriented dimension of climate literacy, particularly relevant for pre-service teachers as future role models. Items were adapted from established environmental behaviour instruments and contextualized for climate change.

To construct the composite Climate Literacy Index (CLI), knowledge and behaviour scores were normalized to a common 0–1 scale and then averaged, giving equal weight to both components. The resulting CLI ranged from 0 to 1, with higher values indicating greater overall climate literacy. The CLI was used as the primary outcome variable, representing the joint presence of climate understanding and climate-responsible action.

Results

RQ1: Information Sources Used And Influence Of Environmental Education

Pre-service teachers reported relying on a combination of digital, institutional, and traditional media sources for climate change information, with clear differences in frequency of use. Digital platforms dominated: the internet was the most frequently used source ($M = 3.17$ on a 1–4 scale, approaching “often”), followed by social networks ($M = 2.76$). Formal education also remained influential, with school-based sources reported at relatively high levels ($M = 2.84$). Books

constituted another important channel (M = 2.65), while family and friends played a more moderate role (M = 2.59), suggesting some informal discussion but not a primary reliance.

Institutional and legacy media were used less frequently. Government services (M = 2.27) and magazines/newspapers (M = 2.24) fell between "rarely" and "sometimes." Television occupied a similar mid-range position (M = 2.41), whereas museums and zoos were less commonly cited (M = 2.14). Cinema and radio were the least utilized sources, with mean values of 2.03 and 1.91 respectively, indicating that audiovisual and broadcast media play a comparatively minor role in shaping climate information practices among pre-service teachers.

Figure 11. Frequencies of climate information sources.

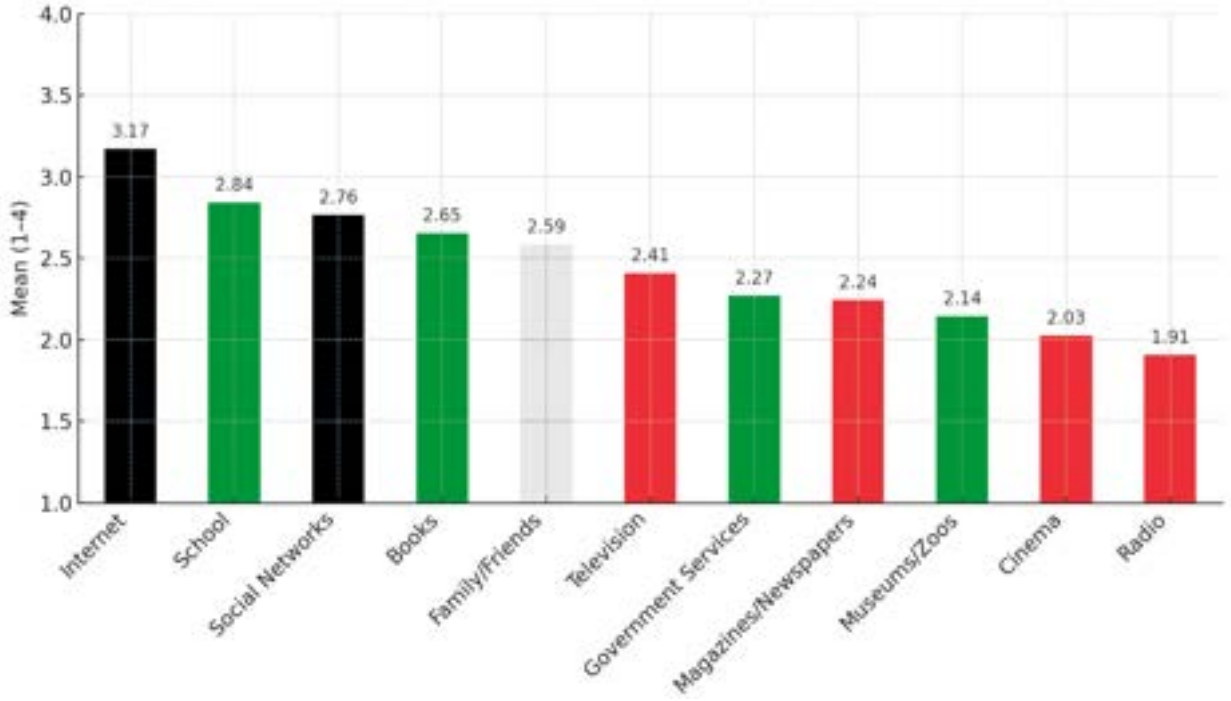


Table 2. Mean frequency of use of climate information sources with and without formal environmental education. (Scale: 1 = Never, 4 = Often).

Climate Information Source	Mean (With EnvEdu)	Mean (Without EnvEdu)	p-value
Internet	3.25	3.10	0.048
Social Networks	2.85	2.69	0.045
Books	2.73	2.59	0.038
Government Services	2.42	2.14	0.007
Magazines/Newspapers	2.65	2.54	0.062
Family/Friends	2.50	2.48	0.081

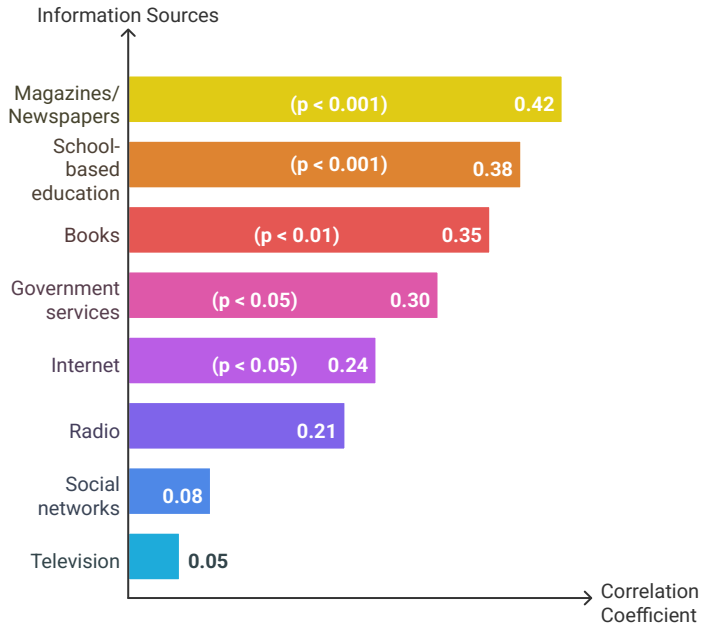
Table 2 summarizes the comparison of source usage means between those who have had formal environmental education (EnvEdu group) and those who have not. Several significant differences emerged. Pre-service teachers with an environmental education background reported greater use of authoritative sources such as books and government services, compared to those without such background. For instance, the EnvEdu group had a higher mean frequency for using books as a climate information source (Mean = 2.73) than the No EnvEdu group (Mean = 2.59), a difference that was statistically significant (p = .038). Similarly, use of government or scientific agency sources was higher among those with environmental education (Mean = 2.42 vs. 2.14, p = .007). Interestingly, those with environmental education also showed slightly higher usage of online

sources: they reported using the internet (general web resources) more often on average (3.25 vs. 3.10, p = .048) and similarly for social media (2.85 vs. 2.69, p = .045) compared to the group without environmental education. This suggests that students who had prior environmental lessons might be more engaged overall in seeking out climate information from a variety of sources (possibly due to greater interest or awareness of climate issues). In contrast, for sources like magazines/newspapers and family/friends, the differences between groups were small and not statistically significant (e.g., 2.65 vs. 2.54 for magazines, p = .062; 2.50 vs. 2.48 for family/friends, p = .081, both n.s.). Traditional media (TV, radio, films) had generally low usage in both groups, with no notable differences.

RQ2: Predictors Of Climate Literacy (CLI) – Information Sources, Education, And Demographics

To assess climate literacy beyond knowledge scores, we constructed a Climate Literacy Index (CLI) that integrates both climate knowledge (the respondents' score on climate-related questions) and pro-environmental behaviours, as described above.

Figure 12. Correlation of CLI with climate info sources.

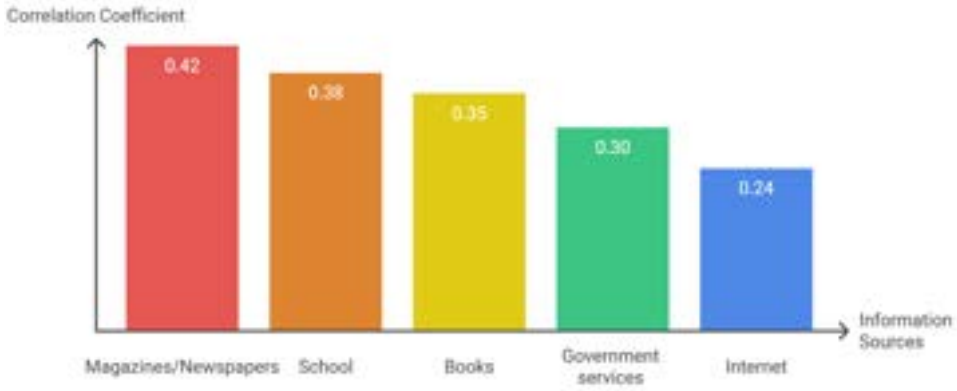


Examining the relationship between information sources and CLI, we found that magazines/newspapers (r = 0.42, p < 0.001) were the strongest positive predictors of CLI, followed by school-based education (r = 0.38, p < 0.001). In contrast, television (r = 0.05, p = 0.48) and social networks (r = 0.08, p = 0.35) showed weak or negligible effects (Figure 2).

Formal nvironmental education had a significant but complex impact. Individuals with environmental education scored higher on CLI (p = 0.0255, t-test). However, multiple regression analysis showed that when examining information sources, formal education alone was not an independent predictor of CLI.

Demographic variables also influenced CLI, with higher education levels (r = 0.41, p < 0.001) and political orientation (r = 0.33, p < 0.01) being the strongest predictors. In contrast, income (r = 0.18, p = 0.08) and gender (r = 0.09, p = 0.31) showed weaker and non-significant effects.

Figure 13. Correlation between Information Sources and Climate Literacy (CLI).



RQ3: Trust In Scientific Institutions And Climate Literacy

When comparing individuals who rely on scientific institutions (universities, government research bodies, and meteorological services) vs. social media users showed significant differences in climate literacy scores. CLI scores for scientific institution users were 18% higher than for social media users. A t-test comparing CLI scores between these groups found $t = 5.37$, $p < 0.001$. Regression analysis further confirmed that reliance on scientific sources significantly predicts CLI ($\beta = 0.41$, $p < 0.001$), while social media reliance has a negative association with CLI ($\beta = -0.27$, $p = 0.002$).

A correlation analysis between social media reliance and common climate misconceptions found that social media users were more likely to believe false climate claims:

"Snowfall disproves global warming" ($r = 0.38$, $p < 0.01$)

"Climate models are unreliable" ($r = 0.34$, $p < 0.01$)

"Climate change is natural and not caused by human activity" ($r = 0.29$, $p = 0.02$)

Trust in scientific institutions is strongly associated with higher climate literacy levels. The highest correlations with the Climate Literacy Index (CLI) were found for Trust in Scientists ($r = 0.47$, $p < 0.001$), Trust in Meteorological Services ($r = 0.42$, $p < 0.001$), and Trust in Scientific TV Programs ($r = 0.39$, $p < 0.01$). Individuals with higher trust in scientific institutions had significantly higher CLI scores than those with low trust. A t-test comparing high vs. low trust groups revealed a significant difference ($t = 4.21$, $p < 0.001$), with high-trust individuals scoring, on average 14% higher on CLI score.

Discussion

Information Sources And Climate Literacy

Consistent with prior research, reliance on structured and credible information sources was found to be associated with higher climate literacy, as education and media coverage from reliable institutions significantly enhance climate understanding and policy support (Pan et al., 2023). Participants engaging with formal education, reputable news media, and written science-oriented sources demonstrate stronger climate knowledge, reinforcing the importance of science education and media literacy in fostering acceptance of climate science (Pan et al., 2023; Loy et al., 2020). Reading climate-related articles in newspapers or magazines emerges as a strong predictor of climate literacy, suggesting that self-directed engagement with quality science journalism improves both accuracy and depth of understanding (Loy et al., 2020). In contrast, social media use shows no positive association with climate literacy, supporting concerns that digital platforms

often amplify misinformation and reinforce confirmation biases (Cheng & González-Ramírez, 2020; Cosby et al., 2025). This aligns with research documenting how online environments contribute to spreading organized climate skepticism and undermining scientific understanding (Cheng & González-Ramírez, 2020). Television also shows limited contribution to climate literacy, consistent with findings that generalized or politicized broadcast coverage rarely deepens climate knowledge unless explicitly science-focused (Cosby et al., 2025; Almansa-Martínez et al., 2024).

Trust In Science As A Key Predictor

Trust in scientific institutions is one of the most robust predictors of climate literacy, with global evidence showing that trust in scientists strongly correlates with better climate knowledge and resistance to misinformation (Van Vleet & Fuller, 2024; Cologna & Siegrist, 2020; Cologna et al., 2024). In some studies, trust in science has been found to outweigh formal environmental education as a predictor of climate literacy, highlighting trust as a foundational mechanism for internalizing scientific information (Larrain et al., 2024; Osborne & Allchin, 2024). Research also emphasizes that building trust is critical for effective science communication and education, suggesting that fostering trust may be as important as delivering content in teacher education (Cooper, 2011; Lacey et al., 2017). Meta-analyses confirm that trust in scientists and scientific institutions strongly correlates with climate-friendly attitudes and behaviours, reinforcing the central role of trust in shaping climate literacy (Cologna & Siegrist, 2020). Overall, these findings underscore the importance of cultivating informed epistemic trust to enhance public understanding and engagement with climate science (Osborne & Allchin, 2024; Cologna et al., 2024).

Ideology And Demographic Patterns

Political orientation consistently predicts climate literacy, with more conservative individuals scoring lower on climate literacy indices, reflecting ideological influences on how scientific information is processed even within relatively homogeneous university cohorts (Arroyo-Barrigüete et al., 2023; Hamilton, 2011; Fischer et al., 2022). While outright climate denial is uncommon, ideological differences often appear in the depth of knowledge and perceived urgency of climate change, suggesting cultural cognition shapes interpretation rather than outright rejection of science (Arroyo-Barrigüete et al., 2023; Trémolière & Djeriouat, 2021).

No significant gender differences in climate literacy were observed, indicating a narrowing gender gap among younger populations (Kranz et al., 2022; Zummo et al., 2020). Similarly, income effects were absent in student samples (Kranz et al., 2022).

These findings highlight the importance of addressing political and cultural factors alongside education to improve climate literacy effectively.

Formal Environmental Education: Limits And Implications

Although participants with prior environmental education tended to display higher climate literacy, its effect was not independent in regression models and appeared mediated by information engagement. This suggests that the presence of environmental education alone is insufficient; its impact depends on quality, recency, and integration with active engagement. This finding aligns with research emphasizing that exposure without sustained engagement has limited long-term effects (Trott, 2020; Trott & Weinberg, 2020). For teacher education programs, this underscores the need for integrated, longitudinal approaches rather than isolated coursework.

Implications, Limitations and Future Directions

These findings suggest that formal education alone is insufficient and must be supplemented with

structured, credible knowledge sources. The negative association between social media reliance and CLI highlights the risk of misinformation, emphasizing the need for media literacy in climate education. For pre-service teachers, climate literacy is particularly crucial, as they serve as knowledge transmitters in society. The incorporation of structured, evidence-based climate education in teacher training programs can enhance their ability to evaluate sources critically and disseminate accurate climate information (Stevenson et al., 2013). Finally, the more trust fostered in scientific institutions, the better the negative influence of misinformation can be counteracted, ensuring that pre-service teachers are well-equipped to guide students toward climate-responsible behaviours.

First, the sample was drawn from a single university and largely from one teacher education program within a specific national context, limiting generalizability. Climate literacy, trust, and information practices may differ across countries, institutions, and teaching specializations. Future research should include more diverse samples and comparative designs to examine how disciplinary background, national curricula, and sociopolitical context shape pre-service teachers' climate literacy.

Second, the study relied on self-reported measures for behaviours, information sources, and political orientation, which may be subject to social desirability and reporting biases. Although anonymity was ensured, participants may have over-reported socially valued behaviours or reputable sources. More fine-grained measures of ideology and complementary behavioural or observational data could strengthen future analyses.

Finally, while the Climate Literacy Index (CLI) integrates knowledge and behaviour, it does not capture all dimensions of climate literacy. It does not directly assess higher-order skills such as critical evaluation of information, misinformation detection, emotional engagement, or communication competence. Moreover, validation of the CLI was limited to content review and internal consistency.

Future studies should extend validation using external criteria and consider expanding the index to include skills that are especially relevant to teachers' professional practice.

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Potentials And Challenges Of Serious Games In Environmental And Sustainability Education

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Sustainability challenges are increasingly recognized as "wicked problems" that require complex, non-linear responses and systemic reasoning. Despite this, traditional education often emphasizes linear thinking, leaving a gap in students' ability to engage with the interconnections of social, ecological, and economic systems. This paper investigates the efficacy of Game-Based Learning (GBL) as a method to bridge this gap in higher education. Specifically, the study examines the FRACTALgame, a cooperative strategic board game designed to enhance awareness of Green Infrastructures (GI) and Ecosystem Services (ES) within Alpine ecosystems. Developed through an interdisciplinary process combining the Educational Game Design Model and the Three-Layered Thinking Model, the game targets three domains: ecological knowledge, EU-GreenComp competencies (such as systems thinking), and soft skills. A mixed-methods playtest involving university students revealed significant gains in conceptual clarity. Participants transitioned from vague, aesthetic definitions of GI to functional, systemic understandings. While the cooperative mechanics fostered engagement and mirrored real-world environmental collaboration, the study identified challenges, including cognitive overload from complex manuals and the "nebulous" nature of Ecosystem Services. Results suggest that while serious games are potent tools for cultivating green competencies, they require a structured GBL framework—including educator facilitation and debriefing—to prevent student paralysis when facing systemic complexity.

Keywords: Sustainability education, game-based learning,

Introduction

Sustainability is widely recognised as a *wicked problem*, defined as a complex and multi-faceted challenge that resists linear solutions and requires adaptive and evolving responses (Lönngren & Van Poeck, 2020). Sustainable land management represents a clear example of such complexity. Balancing land and resource preservation with the fulfilment of human needs remains one of the central challenges of contemporary societies (Verburg et al., 2022). Ongoing population growth and consumption patterns continue to intensify pressure on land systems, making sustainable land management essential for maintaining ecological integrity, promoting social justice and wellbeing, and supporting long-term economic development. As articulated in the UN 2030 Agenda, sustainability challenges are characterised by uncertainty, value conflicts, and strong interdependence across social, ecological, economic, and political domains. Addressing these challenges requires not only disciplinary scientific knowledge—such as ecology, biology, chemistry, and physics—but also transversal competences including systems thinking, futures literacy, negotiation, and collaborative problem-solving. These competences are explicitly articulated in the European Sustainability Competence Framework (GreenComp), which aims to equip learners with the knowledge, skills, and attitudes needed to act as agents of change while recognising human embeddedness within natural systems (Bianchi et al., 2022). Systems thinking is identified as a core competence for sustainability, defined as the ability to consider time, space, and context in order to understand interactions within and between systems. Similarly, the PISA 2025 science framework introduces the concept of *Agency in the Anthropocene*, emphasising learners' capacity to understand human–Earth system interactions, evaluate evidence-based

solutions, and navigate uncertainty and limits. However, in traditional educational settings, students are often trained to approach problems through linear reasoning and the isolation of variables. Sustainability challenges, by contrast, are inherently systemic, operating through feedback loops, non-linear dynamics, and delayed effects (Souliotis & Voulvoulis, 2025). When sustainability concepts are addressed in abstract or fragmented ways, learners may develop awareness without acquiring the analytical tools necessary for systemic reasoning and futures-oriented decision-making (Castaño et al., 2025; Weber et al., 2021). This gap highlights the need for educational approaches capable of fostering systems thinking and equipping students to engage meaningfully with the complexity of sustainability issues.

Game-Based Education For Environmental And Sustainability Education

In response, learner-centred and experiential approaches aligned with Environmental and Sustainability Education (ESE) have gained increasing attention. Among these, game-based education (GBE) offers promising opportunities to engage learners in exploring complexity, negotiating trade-offs, and experimenting with decision-making in collaborative settings (Plass et al., 2015). GBE has proven effective in sustainability education by providing immersive and interactive experiences in which learners can apply theoretical concepts in realistic contexts (Bergen & Fromberg, 2009). Environmental serious games integrate game mechanics and narrative structures to foster both scientific and humanistic competences (Fernández-Galeote & Hamari, 2021; Janakiraman et al., 2018). Grounded in an embodied–enactive cognition model, these approaches connect physical and cognitive engagement through game dynamics, supporting transformative learning experiences that translate abstract knowledge into more concrete understandings of environmental systems and behaviours (Plass et al., 2015). Game-Based Learning (GBL), as a pedagogical approach rooted in GBE, refers to the use of games—played and/or designed—as part of instructional activities, with learning as the primary intended outcome (Plass et al., 2015). Educational games, whether digital or analogue, are thus used to convey disciplinary content while simultaneously fostering transversal skills. Serious games, as a subset of educational games, are developed with explicit learning objectives and require an interdisciplinary design process that integrates pedagogy, scientific knowledge, and game design principles (Plass et al., 2015). Empirical studies indicate that well-designed serious games can increase awareness of environmental and social issues, support understanding of ecosystem complexity and decision-making processes, and enhance motivation, engagement, and information retention. By embedding learners in scenarios where decisions have tangible consequences, serious games support the development of key twenty-first-century skills essential for addressing sustainability challenges (Fernández-Galeote & Hamari, 2021). In this paper, we aim to contribute to the discussion on how game-based learning can support sustainability education goals.

Research Objective

This research is driven by the urgent need to bridge the gap in higher education curricula, where, despite growing efforts, many students still lack adequate exposure to sustainability education. Consequently, the research investigates the feasibility of GBL as a method to effectively equip learners with the necessary knowledge and attitudes to address complex sustainability challenges. More specifically we present and discuss potentials and weaknesses of the FRACTALgame, developed as part of an EU-funded project to increase the awareness of young people on Green Infrastructures and their role in supporting ecosystem services and ecosystem conservation in the Alps.

This study investigates the efficacy of serious games in sustainability education by addressing three specific research questions; i) is FRACTALgame effective in teaching specific ecological

contents, such as Green Infrastructures and ecosystem services, ii) which green, social, or emotional skills are most commonly activated from the students' perspective and iii) which skills students utilized with confidence and which were the most difficult to apply during the cooperative experience.

Methods And Materials

For the game-design process, we combined some technical and theoretical principles from the Educational Game Design Model (Ibrahim & Jaafar, 2009) and the Three-Layered Thinking Model (TLTM) (Fong-Ling, & Sheng-Chin, 2008). The EGDM and the TLM have been adopted to design the scientific contents and educational output and how to fit them with mechanics, dynamics, and aesthetics.

Game Characteristics

Table 1. List of the expected educational outcomes and game elements and rules.

Research Domain	Game Rules & Structure	Specific Mechanic / Tool
1. Ecology Knowledge	Rebuild ecosystems and restore their functions. Setup: Players must identify and manage five distinct Alpine ecosystems: mountains, forests, rivers/lakes, agroecosystems, and urban areas.	GI & ES Cards: Using Green Infrastructure (GI) and Ecosystem Services (ES) cards to counter specific threats. Point Cards: Visualizing the loss of "Supporting," "Regulating," "Provisioning," and "Well-being" services through marker placement.
2. EU-GreenComp	Anticipate and mitigate the effects of overexploitation and climate change in the year 2050. Systems Thinking: Navigating interconnections where a loss in biodiversity or soil (Supporting) leads to crises in human health (Well-being).	Threat Deck: Drawing "Extreme Weather Event" and "Overexploitation" cards that intensify systemic collapse. Resiliency Sets: Building a 5-card set (1 GI + 4 ES categories) to achieve long-term ecosystem protection.
3. Soft Skills	Goal: Cooperative gameplay where players "Team up to save Alpine ecosystems". Rules: Players are encouraged to keep hands open so everyone can see the cards in play to facilitate group discussion.	Cooperative Actions: Using moves to trade cards with other players on the same ecosystem to complete necessary sets. Characters Powers: Utilizing four distinct characters (e.g., Expert, Activist) with special powers that must be coordinated to win.

The FRACTALgame is a cooperative and strategic board game. The primary scope of the game is to bridge the gap between theoretical ecology and practical sustainability competencies. The

overall scope of the game is to foster collaboration among players to mitigate the negative impacts of overusing natural resources, rebuild ecosystems to restore their functions, and ultimately save local communities. The gameplay involves players in saving five specific at-risk ecosystems: mountains, forests, rivers and lakes, agroecosystems, and urban areas. To achieve this, players must strategically utilize Green Infrastructure (GI) and Ecosystem Services (ES) cards to address environmental challenges. Its pedagogical structure is divided into three core domains to achieve specific educational outcomes (Table 1).

In terms of ecological knowledge, the game aims to teach players what ES and GI are and how they function, alongside the ecological principles necessary for sustainable land management. Regarding skills and competencies, the game explicitly targets the development of systems thinking, helping learners identify system elements, interconnections, delays, and feedback loops. Furthermore, the cooperative mechanics require players to engage in future scenario building, problem-solving, and critical thinking. Ultimately, the game fosters social competencies by requiring negotiation to design common scenarios and cooperation to face complex future challenges.

Implementation Phase And Data Collection

Starting from the expected educational outcomes we designed two game-test rounds. The playtest of FRACTALgame took place as part of the SO|STA - Lo Spazio dello Stare project, an initiative aiming to enhance the use of green spaces of Matera University campus, involving six university students with different ages (20-20 years old) and backgrounds (Architecture, Urban Planning and science education).

The test sessions took three days (11-13 September 2024) and a total of 6 hours (2 hours for day) were used for the test session. The research employed a mixed-method approach to evaluate the game's effectiveness, utilizing four distinct tools. To measure gains in ecology knowledge, ex-ante and ex-post surveys were administered, grounded in national educational outcomes for secondary schools and civic education guidelines. To examine the stimulation of specific skills, the study used open-ended questionnaires (also pre- and post-game) based on a revised MEEGA+ model, which was aligned with both the EU Green Skills framework and the PISA 2025 Environmental Science Competences. These quantitative measures were complemented by qualitative tools, including a game-logbook for student self-reflection and a focus group session to gather deeper insights.

Results

The preliminary findings from the initial playtest of the FRACTALgame indicate a good level of student engagement and a strong alignment with sustainability education objectives. Quantitatively, the experience was positively received: five out of six participants reported enjoying the game, and four out of six expressed a willingness to play it again. A primary driver of this success was the cooperative dynamic, which players identified as an added value that effectively mirrored the collective efforts required for real-world environmental action. As one participant observed, the "*ability to save an ecosystem collectively represents one of the most educational aspects of the game*".

Conceptual Learning And Aesthetic Utility

The integration of aesthetic design with pedagogical goals proved to be a significant asset. The graphical elements served as more than mere decoration; they functioned as a powerful medium for communicating complex ecological concepts. Results suggest that the game is a potent tool for introducing nuanced topics like GI. Participants demonstrated a marked shift from vague

conceptualizations toward concrete, post-game definitions as demonstrate some of the examples reported in Table 2.

Table 2. Evolution of student conceptualization of Green Infrastructures (GI) comparing pre-game (vague/aesthetic) and post-game (functional/systemic) definitions.

Phase	**Student Conceptualizations of Green Infrastructures (GI)**
Pre-Game (BEFORE)	*"Green areas."*
Question: *Please define what a Green Infrastructure is.*	*"Infrastructures that follow low environmental impact guidelines."*
	"Infrastructures aimed at environmental protection, such as creating green spaces in urban areas."
	"Semi-anthropized spaces designed to enhance and develop ecosystem services for both humans and nature."
Post-Game (AFTER)	*"Human designed structures mimicking nature and enabling ecosystem services across different ecosystems."*
Question: *After playing the FRACTALgame, please define what a Green Infrastructure is.*	*"Natural structures designed by humans with the scope of preserving ecosystems from being altered by human activity."*
	"Structures that contribute to the proper functioning of an ecosystem (green for land/reforestation, blue for marine ecosystems)."

The transition shown **in Table 2 confirms** that the **FRACTALgame** functions as an effective vehicle for translating abstract theory into concrete understanding. This evolution is supported by the game's structural design, which explicitly targets three distinct research domains:

- **Ecology Knowledge:** *P*articipants moved from general "low environmental impact" statements to identifying specific roles in "*preserving ecosystems from being altered by human activity*". Additionally, where initial definitions were focused on "*green areas*," in the post-game responses students recognise GI as "*human designed structures... enabling ecosystem services*". Additionally,
- **EU-GreenComp:** Post-game definitions reflect an understanding of "proper functioning of an ecosystem," aligning with the EU-GreenComp goal of fostering systems thinking.

Skill Activation And Strategic Complexity

Regarding the development of competencies, the study observed a dominance of cognitive and social skills, though these were not immediate. Students noted that moving from linear to systemic reasoning required an iterative process: "*At the beginning... we didn't plan strategically. thinking strategically, understanding how the system works required time*".

The complexity of the mechanics, specifically the Threat Cards, forced students to move beyond static planning. One participant highlighted how these mechanics simulated real-world pressures: "*The cards representing the overexploitation of resources and... extreme weather events pushed to our limits... they required to change strategy, seeing different possible scenarios. Stimulating but challenging even though they were also realistic*".

Similarly, while collaboration was a key strength, it was described as a skill that had to be learned through gameplay:

Gradual Mastery: "Collaboration was the key to win... but it required some turns before we found a good way to strategically collaborate in building our deck".

Iterative Adjustment: "The collaboration wasn't immediate and required some effort, a lot of adjustments and time".

Despite these positive outcomes, the research highlighted significant barriers to autonomous learning. The concept of Ecosystem Services (ES) remains inherently "nebulous" for many students; game mechanics alone were insufficient to fully clarify the link between ES and sustainability. Furthermore, the instructional design presented a hurdle. Participants reported an "*excess of information*" in the manual, which led to cognitive overload

Conclusions

In conclusion, the findings substantiate the potential of serious games as effective instruments for advancing environmental and sustainability education, particularly in cultivating EU green competencies such as cooperative future scenario building. However, the study also revealed significant pedagogical challenges; difficulties in navigating game mechanics and conceptualizing abstract topics like Ecosystem Services indicate that the game cannot function in isolation. Instead, these findings highlight the necessity of a structured Game-Based Learning (GBL) framework where the educator's facilitation and post-game debriefing are critical to scaffolding the learning experience. Implementation in higher education remains complex, necessitating substantial educator expertise and a shift in institutional mindsets. Furthermore, students may find the demand for soft skills, such as negotiation and cooperation—overwhelming, particularly in the absence of extrinsic grade-based rewards. The results suggest that university students outside of specialized programs exhibit a marked deficit in sustainability skills. Consequently, they experience a form of paralysis, where the complexity of systemic interactions hinders their agency despite a willingness to engage. Therefore, it is imperative to advance a systemic ESE that empowers students to construct a new paradigm of sustainability, one that intrinsically links planetary well-being with peace, human rights, and cultural enrichment.

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Designing Future Cities: Using Futures Literacy To Promote Youth Agency

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Cities are at the forefront of the climate crisis, consuming 75% of global resources and driving urgent sustainability challenges. Concurrently, the erosion of democratic norms has created a pressing need to empower young people with skills to envision and shape sustainable futures. This paper explores the potential of futures literacy in informal science education using the 'Design Your Future City' programme as a case study.

'Design Your Future City' is a week-long informal learning initiative for 15-17 year olds, combining workshops and technology demonstrations to address urban sustainability challenges. Students collaborate with experts and local stakeholders to develop and present creative solutions, fostering systems thinking, creativity and agency. Rooted in Design Thinking, the programme aims to enhance futures literacy and emphasise the ethical, social and environmental dimensions of local sustainability challenges alongside scientific and technological solutions.

This mixed-methods study examines four iterations involving 80 students, educators, and civil society partners. Preliminary findings demonstrate the transformative impact of futures literacy pedagogies on students' ability to address sustainability challenges, with student projects showcasing innovative, actionable solutions. Reflective feedback highlights increased critical awareness, creativity, and aspirations for civic engagement.

The study underscores the importance of embedding futures literacy in education to cultivate youth agency and democratise urban planning. This research contributes a scalable model for integrating futures literacy into informal science education to shape sustainable, inclusive urban futures.

Keywords: Agency, Futures-Oriented Science Education, Out-of-School learning

Introduction

Cities are central contributors to the climate crisis, responsible for 75% of global resource consumption, and this figure is projected to rise from 40 billion in 2010 to 90 billion tons in 2050 (Bibri & Krogstie, 2017). Simultaneously, the erosion of democratic norms has contributed to a growing climate of uncertainty about society's capacity to envision and achieve equitable, resilient futures (Howell, et al., 2021). These issues highlight the need to empower citizens, especially young people, with the skills to envision and shape sustainable futures. This has prompted responses from academics, cultural institutions, civic organizations, and community groups to envision alternative futures. This paper explores the role of futures literacy in informal science education programmes.

Using the 'Design Your Future City' education programme as a case study, this paper will explore how futures literacy can empower young people to address sustainability challenges. 'Design Your Future City' is a free week-long programme of workshops and technology demonstrations for 15-17 year old students exploring urban challenges and climate change. The education programme is a partnership between academia and the Dublin City local authority. Students work with city officials and domain experts in mobility, environment and sustainability, participate in hands-on creative workshops to explore city challenges, and develop creative solutions to a sustainability challenge of importance to them. Throughout the programme, technology

demonstrations are integrated to help students analyse the challenges they face and how others have addressed them. This informs the speculative design process and the envisioning of future solutions. The programme takes place in an informal learning setting outside of school time, that students apply to and attend independently. At the end of the week student present their solutions to key stakeholders including leadership in the city council, industry and academia.

The case studies discussed in this paper were developed in collaboration with the EU-funded Critical ChangeLab project. One of the project's key objectives is to strengthen critical democratic education among young people through participatory action research (PAR) and creative methods inspired by the Change Laboratory approach (Engeström, 2015) and critical pedagogies (Freire, 2017). In the examples featured in this paper, the Critical ChangeLab model has been integrated into the 'Design Your Future City'' programme to foster futures literacy and democratic engagement (Council of Europe, 2016)

Research Question And Aims

This paper will address the following research question: What is the potential of futures literacy in informal science education programmes?

To explore this question, the study focuses on three key aims:

- Identifying the barriers and enablers in promoting futures literacy among young people, particularly those from underrepresented groups.
- Examining the impact of futures literacy in informal science education on sustainability education.
- Investigating how futures literacy fosters youth agency in shaping sustainable futures.

Theoretical Frameworks

Futures literacy is increasingly recognised as an essential skill for young people. Häggström & Catarina (2021) argue that in order for young people to develop agency and voice in addressing global crises, they must acquire futures literacy—the ability to imagine and shape the future. UNESCO (2023) similarly emphasises that "being futures-literate empowers the imagination. It enhances our ability to prepare, recover and invent in the face of change" (P.1). Futures literacy is particularly important in the context of sustainability education and working with youth, as Stuart Candy (2020)) noted "our collective future as a species depends on using our capacity to imagine worlds together".

Central to fostering futures literacy is the concept of agency, as it empowers individuals and communities to take informed, purposeful action toward shaping the future. Social Cognitive Theory (Bandura, 2002) provides an initial framework for understanding agency in social contexts. Bandura identifies three forms of agency: personal agency (individual action), proxy agency (influencing others to act), and collective agency (group efforts to shape a shared future). In this project, these frameworks are integrated into the programme design by supporting young people to imagine sustainable futures, and collaborate in acting towards them.

This understanding of agency is developed through Stetsenko's Transformative Activist Stance (TAS) (Stetsenko, 2014). Rather than viewing the world as a fixed context to which individuals adapt, TAS positions the world as "in the making," realised through goal oriented action. From this perspective, agency is not only the capacity to act within existing structures but to transform them in pursuit of socially and ethically desirable futures. Accordingly in this project, the

programme design moves beyond individual foresight skill-building, toward collective, participatory activities in which young people identify issues they care about, articulate preferred futures, and collectively design actions oriented toward social and environmental transformation.

The United Nations' Sustainable Development Goals (SDGs), comprising 17 interconnected goals, aim to address global challenges related to the environment, economy, and society. These goals guide global efforts to achieve sustainability, with SDG 4 focusing on ensuring inclusive and equitable quality education (United Nations, 2015). UNESCO's Education for Sustainable Development (ESD) agenda plays a pivotal role in advancing these goals by fostering critical thinking, global citizenship, and the skills needed to address interconnected sustainability challenges. UNESCO advocates for integrating sustainability into education systems globally, empowering learners to become active agents in shaping sustainable futures (UNESCO, 2020)

Research Method And Design

This research was undertaken through four iterative cycles of the 'Design Your Future City' programme from the 2024-2025 academic year, involving 80 students, 3 researchers, 21 educators, and 2 civil society organisations. Within the programme, youth participate in workshops that draw from methodologies such as design futuring (Howell, et al., 2021), speculative design (Dunne & Raby, 2013), and speculative fiction (Haraway, 2016) as well as workshops that introduce them to scientific, ethical, social and environmental dimensions of local urban planning and sustainability challenges. They subsequently participate in a design sprint to develop and present creative solutions to these challenges, consulting with scientific experts and local stakeholders. Design Thinking—a human-centred problem-solving approach—guides students through five iterative stages: Empathy, Define, Ideate, Prototype, and Test (Razzouk & Shute, 2012).

A mixed-methods research approach was utilised to assess how the programme supported futures literacy development. Data was generated through a set of instruments, including pre- and post-programme surveys of participating students to measure attitudinal and cognitive shifts; facilitated focus groups conducted at the end of each programme iteration to capture participant experiences and perspectives; analysis of learning artifacts to assess conceptual engagement; and structured workshop observations conducted by a research observer to document pedagogical processes and interactions. These instruments were used in combination to examine participants engagement with futures literacy practices, expressions of agency and approaches to sustainability challenges across programme iterations.

Findings

Findings indicate that futures literacy exercises increased young people's confidence in articulating their vision of sustainable urban planning. Artefact analysis showed students actively designed future-oriented solutions to sustainability challenges, highlighting youth perspectives on issues such as public green space accessibility and air pollution caused by car dependency. For example, one student project, 'Traffic Jam,' proposed an interactive light installation to create safer movement through urban space, reflecting a desire to travel independently that was articulated by participants in workshop discussions. This student project illustrates how futures literacy—i.e. using a desired sustainable future to innovate in the present—cultivates systems thinking and creative problem-solving, both important sustainability competences (Bianchi et al., 2022). In the above example, the concept generated was taken up for further exploration by a local authority, with a student engaging through a short work placement. This offers an initial indication of how futures literacy practices may open pathways for youth participation in

institutional sustainability contexts.

Across participant reflections and post-programme surveys, recurring themes included increased critical awareness, creative confidence, and attention to systems-level aspects of urban challenges. A participant reflected:

> "The week really opened my eyes to the amount of things that need to be considered when trying to solve a problem. You have to think about people it will affect, the environment, different ethical issues, but I found that I really enjoyed thinking about all these things. It is something that I would like to do in the future. Before this I thought of urban planning as more just deciding where to put houses and buildings, now see how much technology is involved in it."

This reflection aligns with the aim of fostering futures literacy by cultivating systems thinking, creativity, and critical problem-solving skills.

Evaluations of the case studies indicate that futures literacy methodologies support critical reflection on eco-social challenges (Maxwell et al., 2019) foster inclusive values (Millsap-Spears, 2018) and encourage imaginative problem-solving (Hardy, 2019).

Discussion

The 'Design Your Future City' programme, uniquely utilising design thinking, and the Critical Change Lab method provides valuable practice implications by offering a scalable model for promoting futures literacy into science education. Grounding sustainability education in place based, future-focused scenarios, promotes a deeper understanding of how individual actions can shape local environments. By encouraging students to envision the future of their area and take action based on that vision, the programme supported young people's sense of agency by helping them see themselves as having the ability to shape a sustainable futures in their area.

Practical insights from implementing the programmes with different cohorts across different learning environments have informed our understanding of the barriers and enablers to imagining alternative futures and fostering futures literacy in informal science education programmes. The impact of the learning space, the methods used, and the facilitation styles can be observed in the futures imagined and solutions presented as part of the programme. These insights, alongside evaluation using a mixed-methods approach (Rincón & Díaz-Domínguez, 2022) provide the basis of our argument that futures literacy is a crucial skill to cultivate in youth.

Future iterations of the programme aim to amplify student impact beyond the programme week by developing their ideas further into pilot projects within the city. This would promote youth agency and create tangible connection between futures literacy and civic action. However, practical limitations exist when transitioning from speculative ideas into feasible solutions, particularly in the risk-averse environment of local authorities.

Conclusion

This case study of the 'Design Your Future City' programme explores how futures literacy might serve as a tool in science education by encouraging young people to envision and create sustainable futures for the areas they live in. At the time of presentation, four iterations of the programme provided a comparative empirical base for examining futures literacy in informal science education. The early findings indicate that futures-oriented, participatory approaches can

create conditions in which young people articulate preferred futures, engage with complex socio-technical issues, and experiment with forms of collective action.

Building on these insights, future research will focus on examining how expanded learning environments, such as sustained mentoring, partnerships with civic and community actors, and opportunities for continued engagement beyond the programme week, influence the development of youth agency and futures-oriented thinking. This research will explore how such conditions mediate the translation of speculative ideas into forms of civic action within the constraints of real-world contexts. This focus will contribute to a more precise understanding of how futures literacy is enacted in informal science education, and how it can support young people to see themselves having a role in shaping sustainable futures for their local area.

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Implementation Process And Outcomes Of School Climate Assemblies: Exploring The Views And Perceptions Of Secondary School Students

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Student participation and decision-making are essential to address various complex global challenges such as the climate crisis, biodiversity loss and social inequalities. This study presents the applied research project EDU4CLIM, which aims to involve young people in sustainability issues through the implementation of Climate Assemblies as an innovative and collaborative educational strategy. The main objectives of this research are: 1) to analyse secondary school students' perceptions of the strengths and areas for improvement of the school climate assemblies organised, 2) to explore the changes in their daily actions as a result of their participation and the sustainability competences they feel they have developed. For this purpose, an ad hoc questionnaire was designed and administered to 206 students in 7 secondary schools in the province of Tarragona (Spain) in the school year 2023-24. A descriptive and qualitative content analysis was carried out. The findings show that the assemblies promoted sustainability competences such as collective action and future thinking according to students' perceptions. Teamwork and learning new knowledge were seen as strengths, and aspects to be improved included making the assemblies more dynamic and devoting more sessions to them. Students comment that their participation in the school climate assemblies has contributed to changes in their everyday environmental behaviour. In particular, students highlight improving waste management through recycling. This study shows that assemblies can be an effective pedagogical strategy to promote sustainability competences.

Keywords: climate assemblies, secondary education, sustainability competencies

Context And Relevance To Science Education

Today's societies are characterised by their complexity and globalisation, as they face various global challenges, such as the climate crisis, and economic and social inequalities. To deal with these challenges, individuals and societies must learn how to adapt and take action. Target 4.7 of SDG 4 - Quality Education of the United Nations 2030 Agenda specifically addresses Education for Sustainable Development (ESD) and the importance of schooling and developing sustainability competencies (UNESCO, 2017). Science education for sustainability promotes natural transformation, emancipation and continuous human progress that contributes to positive change towards sustainability (Sterling, 2017).

Conceptual Rationale

EDS is focused on key learning processes such as collaboration and dialogue, systems thinking, continuous innovation of the educational curriculum and active and participatory learning, as well as learning related to asking critical questions, questioning one's values, envisioning future scenarios, responding in an informed manner and exploring the dialectic between tradition and innovation (UNESCO, 2017).

In the school context, sustainability involves reorienting the content, competencies, expected outcomes, and objectives of education (Sterling et al., 2017). To foster these curricular improvements, it is essential to define the sustainability competencies that will enable students to

critically reflect on their own actions. According to Mulà et al. (2022), sustainability competences are the combination of knowledge, skills, attitudes, and ethical values needed to effectively address sustainability challenges.

In this context, one of the increasingly popular deliberative democratic processes related to climate change are citizen climate assemblies. In recent years, school and youth climate assemblies have emerged internationally to give young people a voice and empower them on climate action (Cebrián et al., 2025; Wilson et al., 2024). These processes seek to ensure children's and youngsters' participation and environmental rights are realised, as most policy decision-making processes exclude the participation of the youngest members of society (Reid, 2023).

Research Aims

This research aims to analyse the implementation of school climate assemblies as an innovative method for learning, deliberating, and addressing climate change. The research was conducted in the EDU4CLIM project, a R&D&I project funded by the Spanish Ministry of Science, Innovation, and Universities, and the EU-Next Generation.

The specific objectives of this study are to:

1. Analyse secondary school students' views and perceptions of the strengths and areas for improvement of school climate assemblies.
2. Explore the sustainability competencies that the students have developed due to their participation in school climate assemblies.

Research Method And Design

An ex post facto study was conducted using the interpretive paradigm to analyse secondary students' perceptions of school climate assemblies (Bisquerra, 2019). The research involved 7 schools in Vendrell and Valls (Tarragona, Spain) during the 2023-24 school year, with the intervention occurring from January to May 2024. School climate assemblies were implemented, supported and guided by facilitators and experts, members of the project's research team (Cebrián et al., 2025). The assemblies are structured in three phases:

1) **Learning phase**: includes materials, preparatory activities and the participation of climate change and sustainability experts.
2) **Deliberation phase:** consists of facilitating dialogue and debate among participants on the environmental issues addressed in the assemblies, through collaborative activities.
3) **Decision-making phase:** focuses on facilitating the development of joint and consensual conclusions based on the reflections and discussions of the participants through voting.

Each assembly consisted of four sessions, organised per class group in each participating secondary school.

- **First session:** In each class, four groups focus on different climate change topics (water, energy, biodiversity, tourism and mobility), discussing both positive and negative aspects. They create a conceptual map and develop a decalogue with 10 action proposals for their community. Finally, each student votes on the top 3 priority actions.
- **Second session:** the group class reflects on the most voted actions, then holds a group vote to select the most relevant action for the community. Afterwards, students work in groups to develop and present the chosen action at the Sustainability fair (third session).

- **Third session:** meeting with the political leaders and municipal technicians of the territory to discuss and share the actions proposed and delve into it to then share and disseminate it in a Sustainability Fair.
- **Fourth session:** a Sustainability Fair is organised where all the class groups from the participating schools present their proposed actions, exchanging perspectives and receiving feedback from the political and social actors of the territory on the actions proposed by the students.

In order to determine the perception of secondary school students in relation to the climate assemblies, an ad hoc questionnaire was designed and administered to 206 students after the Sustainability Fair, at the end of educational intervention. The designed questionnaire consists of two parts; the first consists of ten items related to ten competences of the GreenComp framework (Bianchi et al., 2022), with a Likert scale 1→4, namely: Disagree (1), Neither agree nor disagree (2), Agree (3) and Strongly Agree (4). The items of this first part of the questionnaire and their link to the sustainability competences of the GreenComp framework are presented, indicating the competence and its descriptor (table 1).

Table 1. Questionnaire items, sustainability competence and descriptor from the European GreenComp framework.

	The school climate assemblies have helped me to be able to...	**Sustainability competence (acronym) and descriptor**
1	Reflect on my actions and, at the same time, detect whether they are environmentally friendly.	**Valuing Sustainability (VS):** reflect on personal values and assess them in a coherent way
2	Thinking, deciding and proposing ideas that will benefit present generations, like yours, and future generations.	**Supporting fairness (SF):** support equity and justice for present and future generations.
3	Imagine the future that is most favourable to the well-being of the planet.	**Future literacy (FL):** Projecting alternative sustainable futures.
4	Understand an environmental problem from different interconnected perspectives (personal, environmental, cultural and social).	**Systems thinking (ST)**: Address sustainability issues from all points of view.
5	Make decisions in a critical way without falling into false information.	**Critical thinking (CT):** Evaluate arguments and reflect on how they influence thinking.
6	Identify real situations that occur in my village, neighbourhood or town.	**Problem framing (PF):** Formulating current challenges to identify approaches to anticipate problems

7	Change actions in my daily life for the wellbeing of the planet.	**Adaptability (A):** Making decisions about the future in the face of uncertainty and risk.
8	To find out about activities that are organised in my village, neighbourhood or town to improve the environmental situation.	**Political agency (PA):** Navigating the political system and identifying political accountability
9	Recognise the importance of working collectively in groups to solve problems.	**Collective action (CA):** Acting for change in partnership with other actors.
10	Gain initiative and take individual action to solve a climate change problem.	**Individual initiative (II):** identify one's own potential for sustainability and actively contribute to improving the prospects of the community.

The second part includes four open-ended questions related to strengths and areas for improvement of climate assemblies.

The analysis process consisted of creating a frequency table to calculate the percentage of the different levels of agreement or disagreement in relation to the sustainability competences acquired. To analyse the responses to the open-ended questions, a qualitative content analysis was carried out, in which the responses were coded, and the codes were inductively grouped into categories to identify the main strengths and areas for improvement as perceived by students.

Findings And Coherence Of Argument

In relation to strengths, three main categories emerged: 1) new knowledge about climate change and the well-being of the planet, 2) Sustainability Fair and 3) methodology and dynamics. As students emphasised:

> [S74]: That we have proposed things to improve the situation of the planet. (category: New knowledge about climate change
>
> [P120]: A lot of people participated, and it was very cool. (category: Sustainability Fair)

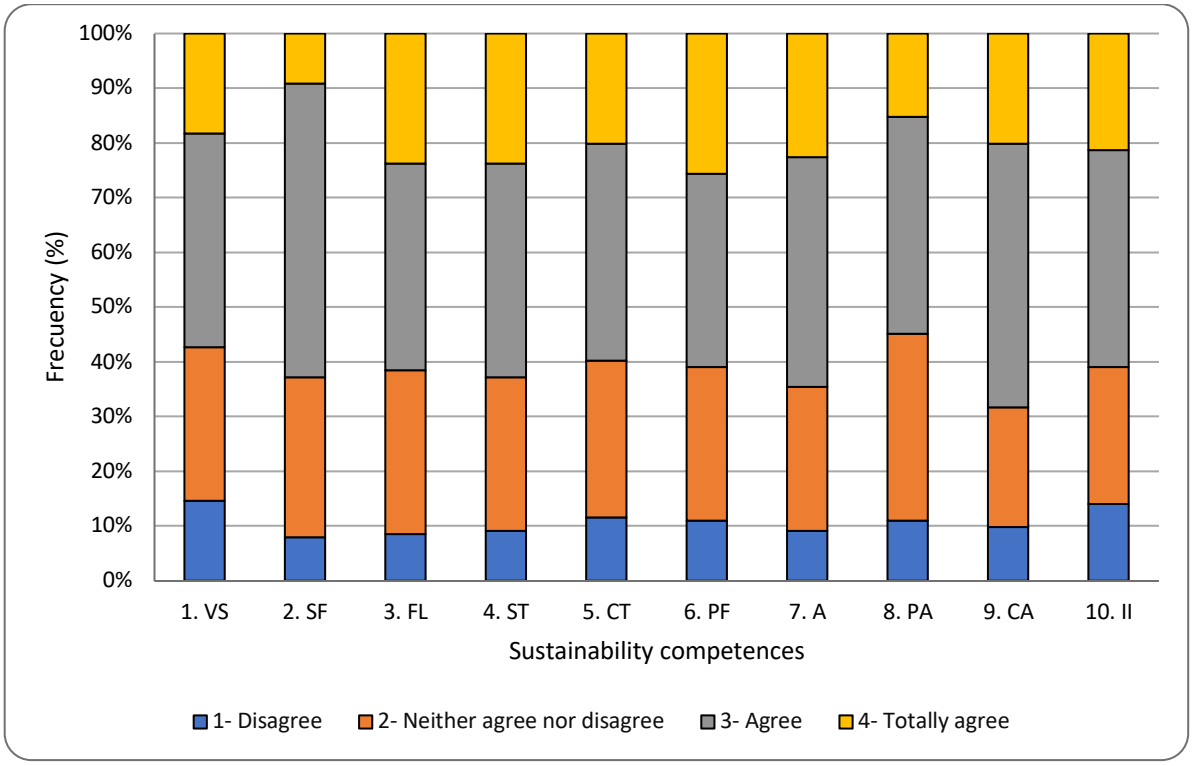
In terms of areas for improvement, two categories emerged, relating to 1) Phases of the assemblies and 2) promoting awareness. As some students commented:

> [S122]: We need to do better at not polluting so much (category: promoting awareness)
>
> [S129]: The topics could be improved, not given so broad a scope. (category: Phases of assemblies)

In line with the acquisition of sustainability competencies, the findings show that the school climate assemblies promoted competences such as collective action (CA), by recognising the importance of working together to find solutions after participating in the assemblies; systems thinking (ST), understood as the ability to analyse environmental problems through multiple interconnected perspectives (personal, environmental, cultural and social) and to recognise the relationships and interdependencies among them; supporting fairness (SF), reflected in thinking, decision-making and the proposal of ideas oriented towards social and intergenerational justice, aiming to benefit both present generations, such as students themselves, and future generations;

and future literacy (FL), related to imagining the most favourable future for the well-being of the planet (Figure 1).

Figure 1. Students' assessment of sustainability competencies acquired in school climate assemblies.



Discussion Of Findings And Implications

According to the first objective focus on analysing secondary school students' views and perceptions of the strengths and areas for improvement of school climate assemblies, the findings of this research show that secondary school students consider the collective action and cooperation promoted by school climate assemblies to be a strength. In terms of areas for improvement, the students consider the dynamism and timing of the assemblies, and the need to extend the sessions and make the topics covered more specific. This is consistent with the findings of previous studies of climate assemblies, which highlight the need to allow sufficient time for deliberation and decision-making (Reid, 2023; Wilson et al., 2024).

In relation to the second research objective, which sought to the explore the sustainability competencies that the students have developed due to their participation in the assemblies, the findings of this study show that students consider that they have acquired various sustainability competences such as collective action and future thinking, which are in line with previous studies. In turn, assemblies promote critical thinking among students, which can help them become aware of climate change and strengthen their engagement and well-being (Trott et al., 2022).

In particular, this research offers contributions for interested academics, teachers and educators, such as a detailed description of the methodological phases used in the assemblies, evidence of the impact of the assemblies on the learning of secondary school students, an ad-hoc questionnaire designed to collect data on the learning achieved in the assemblies from the students' perspective, and documentation of the students' acquisition of sustainability competences following their participation in the climate assemblies from their own perspective.

In response to one of the fundamental questions raised by the ESERA Congress, which is related to living in a globalised society undergoing constant environmental change, there is an urgent need to rethink the role of education in promoting change towards a more conscious society committed to sustainability. In this sense, the implementation of the school climate assemblies presented here could be a very appropriate strategy to support this process, adaptable to different contexts and educational levels.

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ESERA 2025 Copenhagen

Placemaking Reimagined: Examining The Role Of Imagination In Critical Place-Based Learning

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Youth are seldom presented with meaningful opportunities to design their own futures through civic engagement and design, despite their potential as imaginative placemakers. Drawing from critical place-based scholarship, this study aims to reconceptualize placemaking as entwined processes of decolonization, reinhabitation, and imagination. Our work delves into how a critical place-based curriculum empowered youth in imagining and re-envisioning the future of Creekside Plaza, a local plaza-mall under redevelopment. The curriculum supported students' imaginative placemaking through maps, plans, community engagement, and 3D design tools. Although some of the curriculum's activities simultaneously augmented and curtailed youths' creative expression, we argue for the necessary inclusion of youth and their imagination in placemaking roles to design hopeful, vibrant futures.

Keywords: Placemaking, Critical Place-Based Education, Imagination

Introduction

Harvey (2015) speaks to people's collective rights to cities and our rights to (re)make them, where all humans should necessarily share the responsibility for shaping the future of the places we inhabit (Gruenewald, 2003a). Unfortunately, young citizens continue to be excluded from placemaking processes despite instances of youths' authentic contributions to designing for environmental change (Malone, 2013). In this study, we explore placemaking as an integral approach that enables youth to become designers of their own (hopeful) futures as rightful placemakers. We draw from Gruenewald's understanding of placemaking as "the process of shaping what our places will become" (2003a, p. 627). We argue that dwelling in imaginative, "what if" spaces is particularly critical in placemaking, which is an imaginative process in and of itself (Judson, 2019). Furthermore, this conceptualization of placemaking enables children to engage with the sense of possibility for thriving places. Hence, this qualitative study centers the following inquiry: How did youths' imaginative engagement support and constrain their placemaking practices in a local civic design project?

Conceptual Framework: Placemaking As Decolonization, Reinhabitation, And Imagination

Placemaking As Decolonization

Geographical spaces have been exploited as tools of power, domination, and control (Lefebvre, 1997). To restore democratic rights to cities, individuals must first recognize how places represent various histories of struggle and resistance (Cresswell, 2014). Mehrez (1991) writes about decolonization as contesting and liberation from dominant forms of language and ideologies or undoing the hegemonic forces of Western knowledge systems (Shaw et al., 2006). Thus, decolonization requires youth to also critically reflect on their own positions in their local communities to recognize the social and ecological harm imposed on places across temporal scales (Gruenewald, 2003b).

Placemaking As Reinhabitation

Once youth have identified the ways in which their environments have been disrupted through social hegemony, they must learn how to thrive in previously-damaged spaces amongst their

human and more-than-human cohabitants in the present day (Gruenewald, 2003b). Thus, we conceptualize reinhabitation as largely relational work that urges people to practice socioecological care despite powered nature-culture relations that might constrain youths' consideration of more-than-human perspectives. Therefore, we design ways for youth to assume shared collective responsibility towards "intergenerationally connected and morally responsible" multispecies communities (Bowers, 2001, p. 20; Kerkham & Comber, 2013).

Placemaking As Imagination

What distinguishes placemaking as a unique and invaluable practice that instills agency and critical hope in youth is the richness of possibility. However, contemporary schools have become places that suppress young people's imaginative minds rather than nurture them (Benjamin, 2024). Additionally, the romantic nature of imagination often presents questions regarding the legitimacy of imagination as a valid epistemic resource, but Egan (1977) noted that this romantic understanding of imagination is what helps youth make sense of the world in rational ways.

Methods

Study Design

Our team designed a two-week curriculum around critical place-based education and digital storytelling around Willow Creek, a local waterway that flows through a large part of the diverse neighbourhoods of Newtown. We worked with diverse middle school youth (n = 23) from two schools closely located near upstream Willow Creek. Some of the camp activities included: embodied creek play, local map studies on environmental justice, interviews of invited guests and local residents, and the creation of podcasts, zines (short for magazines), and AR (augmented reality) stories about Willow Creek.

We designed this curriculum based on the Connect–Investigate–Interrogate–Imagine–Act (CI^3A) pedagogical framework (Figure 1) developed by Carlone et al. (2024) for critical place-based education. Based on the CI^3A framework, we created opportunities for youth to connect with place through embodied and affective experiences in the field (e.g., care, wonder, joy, and stillness) (Stapleton & Lynch, 2021). We conceptualized investigation as transdisciplinary epistemic practices drawing from science, history, art, and technology. By analysing maps that illustrated relationships between environmental health and social justice, the curriculum also offered opportunities for youth to interrogate the social and environmental inequities that represent distributional injustice (Campbell et al., 2022). To design for imaginative spaces, we supported students' speculative storytelling, futuring, and placemaking practices as youth took on the role as civic designers advocating for just and sustainable futures of Willow Creek. Lastly, we provided space for youth to share their placemaking stories and act as advocates for the Willow Creek community.

Given our research question regarding the role of youths' imaginative work towards placemaking, this paper focuses on the last three days of the larger summer curriculum based on Creekside Plaza, a local area currently undergoing redevelopment located near Willow Creek and students' schools. Students engaged in a series of civic design activities using government-led development plans, local maps, community interviews, and technical tools (e.g., AR). Table 1 further outlines the central activities that took place during the AR civic design unit.

Figure 1. Connect–Investigate–Interrogate–Imagine–Act (CI³A) Framework.

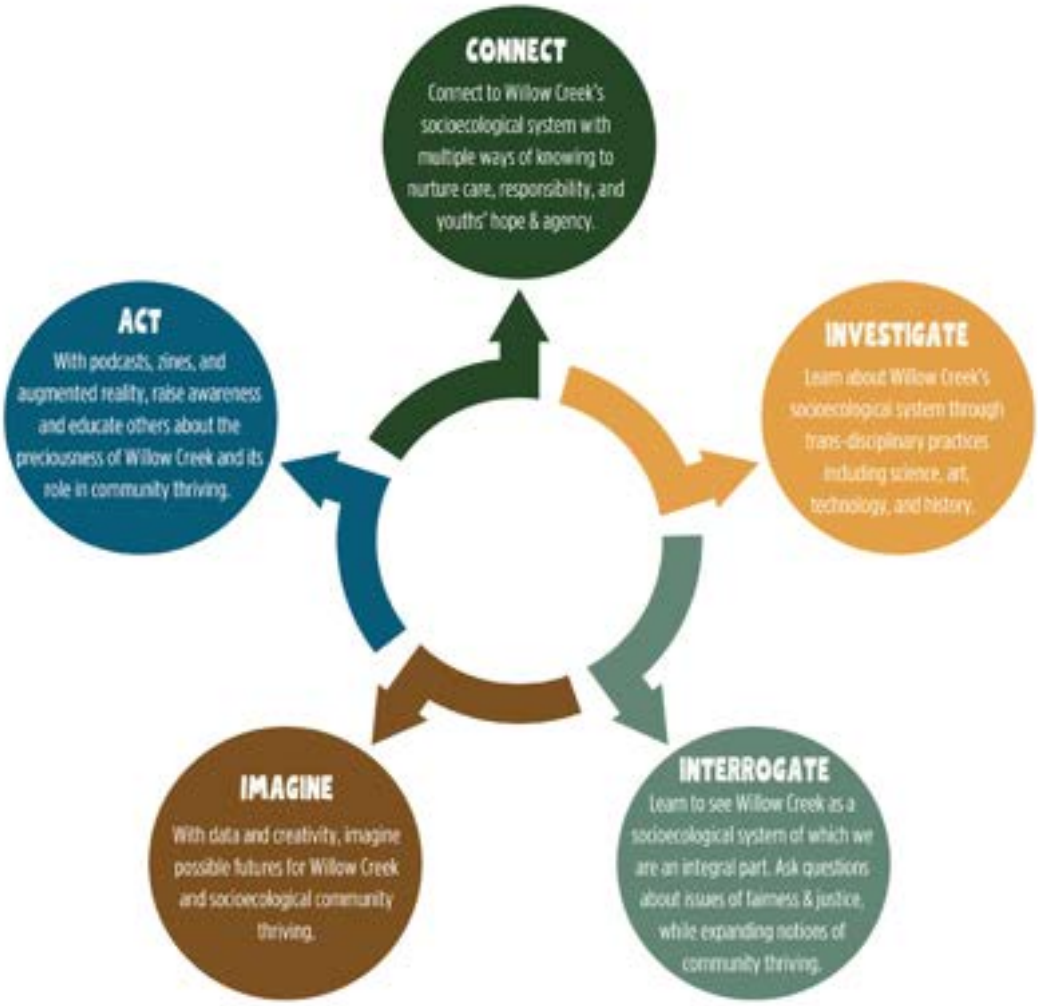


Table 1. Curricular Activities during Civic Design Project with Creekside Plaza.

Creekside Plaza Map Study	Community Eco-Survey	Collaborative Redesign	3D Design with AR
Evaluate government's master plan of Creekside Plaza in small groups	Interview local development professionals and visitors at Creekside Plaza	Generate collaborative proposals to redesign Creekside Plaza	Create individual AR projects that visualize a select portion of group's proposal

Data Collection & Analysis

Our data corpus consisted of video, student artifacts, and end-of-unit interview transcripts. Artifacts included student-created maps, plans, and AR projects that visualized youths' imagined versions of Creekside Plaza. During our first phase of analysis, we examined the videos to identify key moments in the data that informed our understanding of youths' imaginative engagement in the context of placemaking. As a result, we largely focused our analysis around the Creekside Plaza Map Study and Collaborative Redesign activities, creating content logs (Miles et al., 2013) based on those 10 hours of video data as our first "pass" of processing data. We triangulated

multiple sources of data to confirm our emerging assertions about the data. Our team drafted analytic memos related to the purposes, moments, forms, affordances, and limitations of imaginative engagement, and debriefed our analytic decisions with other researchers.

Findings

Playful (But Purposeful) Futuring

About a fourth of our students overtly presented child-like, fantastical assets in their final AR projects. In Nathan's case, his portrayal of a talking racoon named Jim as an environmental advocate illustrates an ontological shift through anthropomorphizing a racoon. He illustrates a vulnerable animal as one with agency, who is eager to educate others about her environment and is passionate about protecting their home. In essence, Nathan is layering his own advocate agenda onto this racoon. Admittedly, selecting a raccoon specifically was a rather fortunate "accident." Although Nathan's selection of a specific species was rather spontaneous, his intent to centre more-than-human advocates was part of his purposeful design: "I kind of just was thinking of someone else besides a human to use, so I just thought of a raccoon. I was just looking through everything, and I just saw a raccoon, and I was going like, "I'm going to use this, and name him Jim" (Nathan). He went ahead and named the racoon and leveraged his imagination to tell Jim's story about "how deforestation is ruining his life almost, and how his home has just been taken away, and it allows him to not be safe."

Figure 2. Nathan's AR Project.



Relational Care: Imagining *For* And *With* Others

Our design of the AR unit challenged youth to centre relationality and care for others. The intergenerational conversations in which adult facilitators modelled relational care and

perspective-taking drove students to design for others. For instance, Ms. Castillo advocated for a "young people hangout spot," such as a bowling alley. Brett pushes back, stating that not all plazas and malls have bowling alleys. Ms. Castillo models perspective-taking: "I know, but if [Creekside Plaza] doesn't have what the community needs, the only place to go is in [central] Newtown. So [as a] college student, if I don't have a car, I don't have anything to do on a Friday night." Realizing that the nearest bowling alley from Creekside Plaza's college campus is 4.5 miles away, Brett soon made space for a bowling alley in their group's proposed design. Throughout the unit, Brett had already emphasized the need to design spaces "for everybody;" yet Brett's engagement with international imagination with adults had augmented Brett's pre-existing values of collective care in their designs of Creekside Plaza.

Material Engagement In Physical And Digital Spaces

Our curriculum designed multiple opportunities for youth to interact with physical (e.g., paper maps) and digital materials (e.g., 3D assets). Youths' interactions with diverse materials allowed to expand imaginative engagement beyond cognitive and ideological spaces, towards material ones. Specifically, our use of AR and virtual visualizations of youths' futured Creekside Plaza offered opportunities for youth to be positioned as co-imaginaries. Ms. Yana noted the affordance of scanning QR codes to students' AR projects: [the audience is] gonna be able to see this world that we're creating," where she positions AR as the object that allows them to become co-visionaries of their imagined worlds. Having physical and digital artifacts when interacting with adults enabled youth to enact their voices and be positioned as advocates within their communities. When interviewing local visitors at Creekside Plaza, Addison's group requested to use their maps during their interactions, which made her "happy because then people would listen to me and stuff." Similarly, Nathan noted the important role of having a technology-enabled design that captures his imaginative work because AR "allows you to go inside of it, and get more detail of stuff" compared to "just words." As such, both physical and digital materials instilled a sense of ownership and confidence in youth as civic designers who were eager to inform adults about their imagined futures.

Conclusions

Our findings inform us about youths' imaginative placemaking during the civic design unit in three notable ways. First, youths' imagination was recognized as a legitimate epistemic resource for placemaking. Second, youth engaged in placemaking through intergenerational care, albeit reproducing anthropocentric values. Lastly, their engagement with and production of materials (e.g., maps, AR) coupled with their imagination further enabled their authority as imaginative placemakers. Though young citizens have been excluded from placemaking processes despite directives towards creating better cities for children (Freeman & Tanter, 2011), we hope this empirical example contributes to the field's understanding of youths' imagination in placemaking towards increased opportunities for youth to act as agentic placemakers in the world.

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A Regression Analysis Of Environmental Attitudes And Interest In Environmental Topics

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The 21st century has been fruitful in contributions and initiatives for the conservation and sustainability of the environment. Environmental concern is visible in public spaces and media, and environmental education has become a cross-cutting aim of science education and general education. However, the relationship between the environmental attitudes and the environmental knowledge is relatively unknown, especially for young people, because this group rarely takes part in sociological environmental surveys, which are usually focused on adults. This study addresses the empirical exploration of this relationship for a large sample of 15-year-old Spanish students who participated in an international project where they answered an environmental attitude scale and rated their interest in some environmental topics. The results show overall positive attitudes and moderate interest in environmental topics, as well as pinpoint the specific best (people should care more about the environment) and worst (science and technology can solve all environmental problems) environmental attitudes and the most (protection of endangered species) and least (improve the harvest) interesting environmental topics. In addition, the regression analysis finds the environmental topics that are the best predictors of the environmental attitudes, which share over 27% of common variance. These results are discussed in light of other studies, and some recommendations are proposed so that science education can effectively contribute to improving the environmental attitudes and the interest in environmental topics, putting especial care into teaching about the worst attitudes, the less interesting topics, and the topics that are negative predictors of attitudes.

Keywords: Attitudes towards the environment, environmental topics, prediction of attitudes, education for sustainability

Introduction

Environmental awareness, concern, or attitudes are central concepts in environmental psychology research that the emergence of climate change has turned into socially relevant and educationally unavoidable issues to promote students' pro-environmental behaviours. According to social psychology, attitudes guide behaviour in general (Eagly & Chaiken, 1993), and environmental attitudes guide sustainable actions, pro-environment behaviours, media consumption, etc. (Liu et al., 2020). Further, environmental attitudes and environmental topics are intersectional and relevant to science education (Braun & Dierkes, 2019).

According to Eagly and Chaiken (1993), attitudes are psychological tendencies that express the evaluation of an entity with a certain degree of approval or disapproval. Obviously, the knowledge of the entity that assesses the attitude must be a key factor of the attitudinal acceptance or rejection degree so that both elements are related. In this case, environmental attitudes are related to people's interest in knowing environmental topics. The evaluative summary of the entity (approval/disapproval; agreement/disagreement; interest/disinterest) is the consequence of the dynamic interaction of the three basic elements of attitudes (cognitive, affective, and behavioural).

As a consequence, environmental attitudes are today a popular topic in media and in sociological surveys (CIS, 2020; European Union, 2014). Further, education for sustainability (ESD) and sustainable development goals (SDG) permeate all the educational levels and subjects of general education and science education in particular (UNESCO, 2006; UN, 2015). Thus, the investigation of environmental attitudes constitutes today a wide field of research and education.

Most of the research literature admits that environmental knowledge contributes to developing sustainable behaviours and attitudes, but that knowledge by itself does not produce these developments, so research is needed to determine the contexts and influences of knowledge on environmental attitudes and behaviours (Braun & Dierkes, 2019). Further, although a direct correlation between environmental knowledge and environmental attitudes is generally admitted, consensus on the best measurements of environmental knowledge is scarce, and no model is considered proven (Makki et al., 2003; Liu et al., 2020).

Interest in topics is key to attaining some knowledge and the Krapp and Prenzel's (2011) concept of interest as a particular case of the conceptualization of attitudes is adopted in this study, which addresses the diagnosis of environmental attitudes and analyses its relationship with the interest in environmental knowledge topics within the framework of science education.

The conceptualization of the environmental attitudes construct assumes the original psychological sources and is operationalized here through a specific and simple measurement tool, which is based both on its relevance for science education and on its systematic approach to the multidimensional and hierarchical nature of environmental attitudes, as suggested by psychological literature (Cruz & Manata, 2020; Milfont & Duckitt, 2010).

Data on environmental attitudes and interest in environmental topics are taken from the database of the international comparative study The Relevance of Science Education Secondary (ROSES-2022). ROSES explores 15-year-old students' science attitudes and their relevance for science education around the world (Jidesjö et al., 2020).

The research questions of this study are twofold:

What are young students' environmental attitudes and interests in environmental topics today?

Which environmental topics are the best predictors of environmental attitudes?

Methodology

Materials

This study draws its data from the questionnaire applied worldwide as the tool of the international project The Relevance of Science Education Second, which explores several categories of students' experiences that may be relevant to science education. An international group of experts developed the research survey for the ROSES-2022 project (ROSES-Q). This study elaborates on data from two categories of this survey to answer the research questions (Jidesjö et al., 2020).

The environmental attitudes are operationalized from the category of ROSES-Q "Me and the environment,", which contains 13 different attitudinal statements about the environment (Figure 1). For each statement, students are asked to answer the following question: To what extent do you agree with the following statements? The students tick their answers on a 4-point Likert scale, whose points are coded as follows: 1-disagree, 2, 3, 4-agree. The confirmatory factor analysis of this category (CFI = .964; TLI = .941; RMSEA = 0.068), within the framework of relevance for science education of the ROSES project, confirms a latent structure of a single factor formed by 6 items (D2, D4, D5, D6, D9, and D13) with statistically significant loadings and good internal consistency (ordinal Omega=.769).

Likewise, data from the interest in 14 environmental knowledge topics, which are taken from the category of ROSES-Q labelled "Things I would like to know more about." All items display environmental content (i.e., "E11. How to protect endangered species"), and the participants are asked to answer the following question about the topics: How interested are you in learning more about this topic? The students tick their answers on a 4-point Likert scale, whose points are coded

as follows: 1-not interested, 2, 3, 4-very interested). The environmental knowledge is elaborated in this study as the students' interest along those 14 items (Figure 2).

The ROSES-Q items are enacted as direct, clear, simple, and short sentences (averaging eight words), mostly written in an affirmative and positive style, although some are written in a negative way to compensate for response bias.

Participants

A valid sample of 1912 Spanish students was surveyed through the ROSES-Q following the protocols of the ROSES project, whose target population is 15-year-old students (grades 9 and 10). They identified themselves as girls (49.4%), boys (46.9%), or did not indicate their sex (3.7%), and attended 23 schools (14 public and 9 private) throughout a Spanish region. Almost all (97.2%) were aged between 14 and 16 years old (mean age 15.1 years), and no one received incentives for participating.

The approval of the ROSES project by the Spanish State Research Agency implied the commitment to comply with the ethical principles and the relevant national, European, and international legislation on human rights. Students were informed that answering meant consent to participate, that they could leave items unanswered, and that the survey was anonymous.

Procedures

The students answered the ROSES-Q online as a class assignment directed by their teachers within their class group and applying the same protocol. The researchers did not have any personal contact with the participants, and the teachers did not have access to the database, warranting total anonymity.

The data gathering took place between late 2020 and 2024, and some data cleansing procedures were developed to improve the quality and validity of data through controlling and deleting invalid answers (homogeneous, highly incomplete, joking, random responses, etc.).

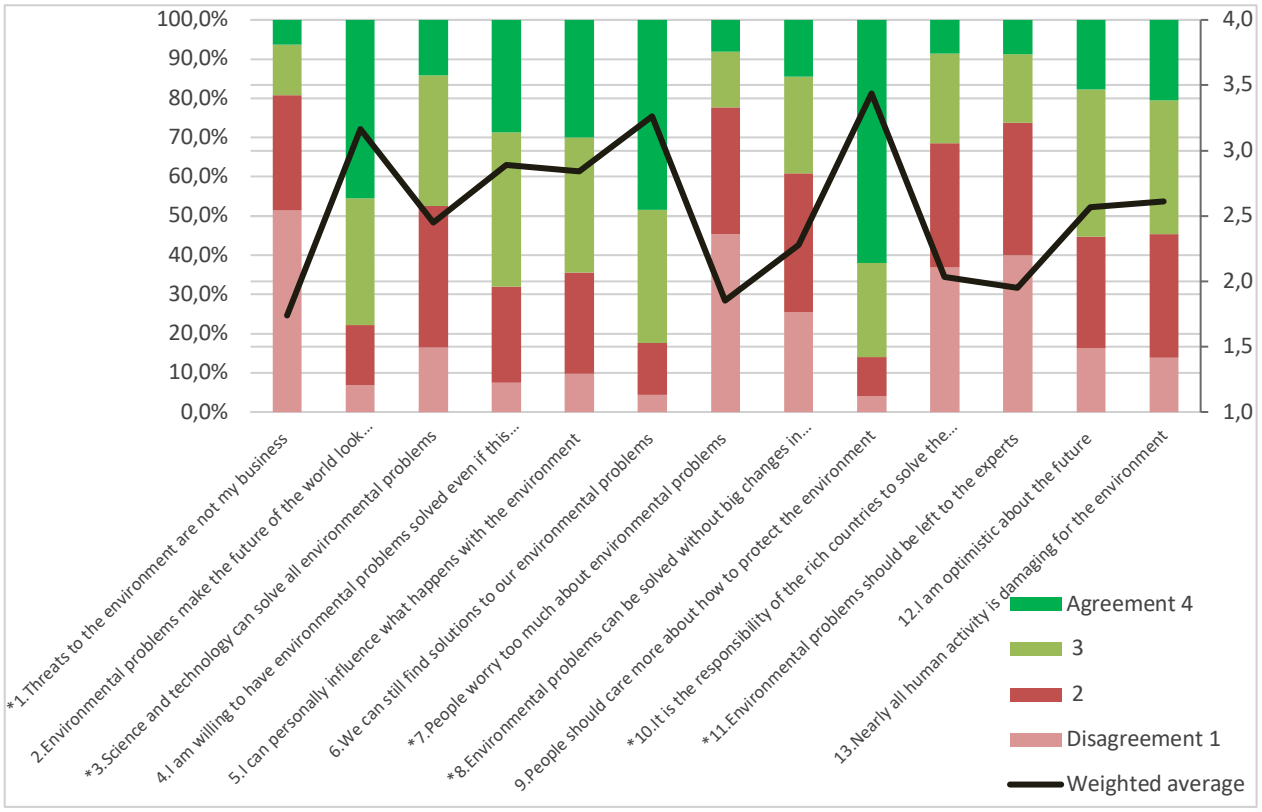
The mixed method, quantitative and qualitative, applies to students' responses. The percent and the weighted average of the Likert scale points quantify the valid responses. The latter is a fertile parameter for simply representing items and visualizing comparisons.

Six items from the category "Me and the environment," marked with asterisks in the figures (i.e., environmental threats are not my business), present content that is contrary (negative/anti-environment) to the direction of the remaining items (consciousness/pro-environment). The scores of these dysfunctional items must be interpreted in a complementary or reversed way to the functional/positive pro-environmental items so that the interpretation of all item scores has the same homogenous pro-environmental meaning throughout the scale.

Results

The first comprehensive finding of this study is the identification of globally positive environmental attitudes, since the responses to the functional statements of the category "Me and the environment" are above 50% global agreement (weighted averages greater than 2.50), and the dysfunctional phrases are below 50% global agreement (weighted average less than 2.50) (Figure 1).

Figure 1. Percentages of responses on each of the four points of the Likert scale (left vertical axis) and weighted averages (right vertical axis) of the 13 items of the category "Me and the environment" and the three complementary phrases.



* Items expressing anti-environmental content.

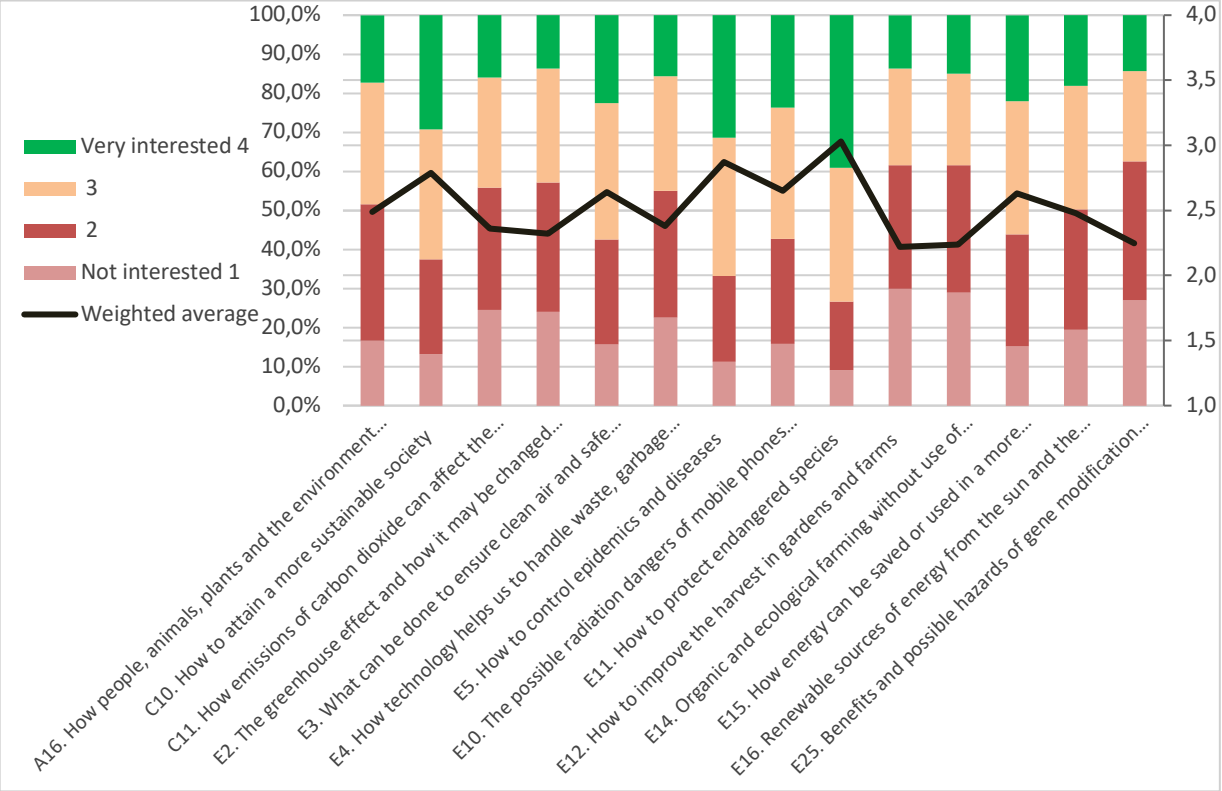
Another finding is the identification of the specific aspects that arouse the most and least favorable environmental attitudes, that is, the main strengths (agreement greater than 80%) and the weaknesses (lowest agreement) of the environmental attitudes. Three items reach the most favorable environmental attitudes scores, largely agreeing that people should feel more concerned about protecting the environment (D9, D7 reversed) and the ability to still find solutions to environmental problems (D6, D4) and largely disagreeing that environmental threats are not my concern (D1, D10, D11 reversed).

The item "D3. Science and technology can solve all environmental problems" reaches the lowest agreement rate though it is intermediate (48%; average 2.45). The remaining items display agreement scores in-between those already mentioned (note that the reversed interpretation of disagreement also applies to D8).

In regard to the students' interest in the 14 environmental topics surveyed, it could be described as moderately positive, since most of the issues reach interest percentages above 50% and weighted averages higher than the midpoint (2.5) of the Likert scale (Figure 2).

It is worth highlighting the large interest in the items about the protection of endangered species, the control of epidemics and diseases, and the path towards a more sustainable society. On the other hand, the lowest interest refers to the topics related to agricultural issues (improving crops, genetically modified organisms, and organic and ecological agriculture). The remaining eight environmental topics display intermediate interest scores that are placed between those rates achieved in the previous extreme issues.

Figure 2. Percentages of responses on each of the four points of the Likert scale (left vertical axis) and weighted averages (right vertical axis) of the 14 environmental topics.



Correlational Analysis

Most of the Pearson correlation indices between the scores of the environmental attitudes items and the items of the environmental topics reach statistical significance (Table 1).

The inspection of the correlation indices (Table 1) allows us to appreciate some general features regarding the relationships between the environmental topics and environmental attitudes.

First, the environmental attitude items displaying the highest correlation indices with the environmental topics are those items that were mentioned in the structure of the environmental attitudinal category as the most significant attitudinal in relation to the relevance of science education (D2, D6, D9, D5, D4, and D13 items).

Second, the group of attitudinal items with negative formulations clearly exhibits the lowest correlations (close to zero or negative) with topics. Item D1 (Threats to the environment are not my business), of this group, displays the lowest correlation of all.

For their part, the environmental topic items generally present a pattern of correlations quite similar among them, except for item A16 (How persons, animals, plants, and the environment depend on each other), which stands out for having significantly lower correlations compared to the others.

All in all, according to the former Pearson correlation analysis between environmental attitudes and topics, the environmental attitudes display highly different Pearson indices among them, whilst the differences of the environmental topic correlations seems much more homogeneous among them.

Linear Regression

Some linear regression analyses were performed. The total environmental attitude score obtained by adding some environmental attitude items (after reversing the scores of the dysfunctional items) is the dependent variable, and the environmental topics are the independent variables

(predictors).

Table 1. Pearson correlation indices between the scores of the environmental attitude items and the environmental topic items.

Attitudes	Environmental issues													
	A16	**A10**	**A11**	**C2**	**C3**	**C4**	**C5**	**C10**	**C11**	**C12**	**C14**	**C15**	**C16**	**C25**
1	-.055*	-.125**	-.112**	-.078**	-.079**	-0.042	-.104**	-.072**	-.134**	0.018	-0.012	-.093**	-.051*	-0.032
2	.145**	.219**	.149**	.206**	.228**	.118**	.242**	.187**	.271**	.102**	.114**	.197**	.136**	.091**
3	.073**	.114**	.158**	.142**	.117**	.216**	.104**	.053*	.052*	.090**	.085**	.119**	.157**	.130**
4	.223**	.349**	.291**	.324**	.345**	.230**	.278**	.304**	.360**	.230**	.256**	.303**	.276**	.211**
5	.190**	.290**	.255**	.262**	.265**	.222**	.257**	.250**	.289**	.159**	.207**	.275**	.245**	.179**
6	.154**	.215**	.183**	.160**	.213**	.147**	.305**	.165**	.243**	.093**	.128**	.202**	.172**	.128**
7	-0.029	-0.032	-0.003	0.014	-0.030	.062*	0.000	-0.022	-.106**	.100**	.062*	0.016	.076**	.066*
8	.061*	0.050	.084**	.074**	.106**	.155**	.106**	.084**	.056*	.114**	.115**	.086**	.097**	.110**
9	.179**	.290**	.213**	.230**	.279**	.172**	.308**	.236**	.363**	.118**	.135**	.252**	.170**	.106**
10	0.035	.061*	.097**	.140**	.112**	.147**	0.037	0.021	0.002	.122**	.124**	.109**	.136**	.140**
11	-0.007	-0.010	0.040	.069**	0.048	.105**	-0.014	-0.014	-.071**	.118**	.081**	.061*	.100**	.107**
12	.103**	.096**	.137**	.087**	.147**	.150**	.113**	.088**	0.042	.138**	.137**	.111**	.148**	.128**
13	.116**	.159**	.135**	.209**	.160**	.149**	.135**	.150**	.182**	.152**	.167**	.181**	.144**	.129**

** p < .01. *p < .05.

The first linear regression analysis computed the total environmental attitudes score as the sum of all 13 items of the environmental attitudes scale (after reversing the dysfunctional items). The predictors (14 environmental topic scores) explained 22% of the environmental attitude variance (R^2), yet many predictors did not attain statistical significance. After eliminating the non-significant predictors, some different regression analyses were tried, but their estimators did not improve at all.

The second linear regression analysis computes the total environmental attitude score (dependent variable) by summing just the items (2, 4, 5, 6, 9, and 13), those obtained by confirmatory factor analysis. The linear regression analysis with all 14 environmental topics as predictors yields a model with 27.6% shared variance and four non-significant predictors. After removing the four non-significant predictors, the model (nine predictors) is more parsimonious and increases the shared variance to 28.8% (corrected $R^2 = 28.4\%$). Seven predictors display positive standardized regression coefficients, where the highest regression coefficients correspond to the three most interesting issues, and two negative predictors correspond to two of the three least interesting issues (Table 2).

The strongest predictor of environmental attitudes is the item E11 (How to protect endangered species), which also has the highest interest rate. The weakest predictor of environmental attitudes (absolute score of its estimator) is the item E10 (The possible radiation dangers of mobile phones and computers). It is also worth highlighting the two negative predictors (E4. How technology helps us to handle waste, garbage, and sewage; E12. How to improve the harvest in gardens and

farms).

Table 2. Linear regression model of the environmental attitudes (6-item empirical factor as dependent variable) with respect to environmental topics (significant predictors p < .05).

Predictors (environmental topics)	Estimator	p	Standard Estimator
Constant	11.317	< .001	
E11. How to protect endangered species	0.873	< .001	0.2353
C10. How to attain a more sustainable society	0.534	< .001	0.1510
E5. How to control epidemics and diseases	0.483	< .001	0.1329
E2. The greenhouse effect and how it may be changed by humans	0.451	< .001	0.1250
E3. What can be done to ensure clean air and safe drinking water	0.257	0.035	0.0722
E15. How energy can be saved or used in a more effective way	0.260	0.021	0.0717
E10. The possible radiation dangers of mobile phones and computers	0.218	0.028	0.0614
E4. How technology helps us to handle waste, garbage, and sewage	-0.303	0.007	-0.0843
E12. How to improve the harvest in gardens and farms	-0.340	< .001	-0.0958

All in all, the main finding of these analyses is the evidence of the overall significant and mainly positive empirical relationship between environmental attitude items (reversing the scores of negative items) and environmental topic items. Then, the regression model for the 6-item environmental attitudes (dependent variable) shows nine significant predictors, where strongest predictors are just the four most interesting environmental topics.

Discussion and conclusions

The discussion focuses first on evaluating the contribution of the results to answering the research questions. The surveyed students displayed globally positive environmental attitudes because they highly agree with the functional statements and disagree with the dysfunctional statements.

Further, the students' interests in environmental topics are also positive, but the interest-weighted mean scores are a bit lower than the environmental attitudes' agreement scores. The largest interest is displayed by the items about the protection of endangered species, the control of epidemics and diseases, and the path towards a more sustainable society. The lowest interest is displayed the topics related to agriculture (improving crops, genetically modified organisms, and organic and ecological agriculture).

In summary, the answer to the first research question is that young students hold clearly proactive environmental attitudes, while interest in environmental topics is positive, yet a bit lower and much dependent on the specific topic being considered. These overall findings on environmental attitudes confirm the results reported by Sa-ngiemjit et al. (2022) employing a sample from the same Spanish region and same age.

In the long run this study poses a fundamental question of social psychology (Eagly & Chaiken, 1993), namely, the degree that the knowledge of the attitude entity (in this case, the environment, represented by 14 environmental topics) influences the related attitudes (in this case, environmental attitudes). This question has been explored here through some correlational analyses that contribute to empirically confirming the relationship as well as to highlighting some weaknesses that provide implications for improving the educational practices on education for sustainability and sustainable development goals (UN, 2015).

The overall correlations between environmental attitudes and interest in environmental topics are significant and positive (after reversing scores of the dysfunctional attitudinal items), which gives support to the overall positive relationship between environmental attitudes and interest in environmental topics.

The linear regression analysis that takes the 6-item reduced empirical factor of environmental attitudes as the dependent variable demonstrates the significant empirical relationship between environmental attitudes and interest in environmental topics. A parsimonious prediction model consisting of nine significant environmental topics as predictors was found, where environmental attitudes and environmental topics share a significant proportion of common variance (28.8%). These results reinforce similar findings reported by Makki et al. (2003) and Liu et al. (2020) and allow drawing some educational consequences.

The implications of these results for the educational practice on sustainable development quality emphasize, as compensatory education, the careful educational planning of the less appreciated aspects of environmental attitudes and environmental topics (improving crops, genetically modified organisms, and organic and ecological agriculture) as well as of the topics identified as negative predictors of environmental attitudes (UN, 2015). The two predictor topics that display negative yet the lowest regression coefficients (garden and farm harvesting and waste management) suggest that this negative relationship may be a consequence of the invisibility of food and waste production in the current urban societies, in spite of being central elements for the sustainability of the planet. Further, in spite of the fact that mean environmental attitudes are overall positive, a minority group of students, ranging from 20% to 40% depending on the environmental attitudes item (Figure 1), hold negative environmental attitudes, so that this group should also be the preferential focus of a quality compensatory environmental education.

The main limitations of this study stand on the fact that its design is based on ROSES-Q, which provided the items on environmental attitudes and environmental topics, and these items were not specifically designed for the research questions posed in this study. For instance, the approach to environmental knowledge (as interest in environmental topics) is a bit different from the usual one, which often focuses on quantitative curricular knowledge rather than qualitative interest in knowledge (Braun & Dierkes, 2019). However, the findings are functional, since the regression confirms the empirical contribution of interest in environmental topics to predict the environmental attitudes, through the shared variance is moderate.

Finally, this study contributes a brief and reliable environmental measurement scale with universal meaning to environmental attitudes research. Further, the study opens a new approach to environmental topics through interest rather than traditional content knowledge scores.

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Exploring Competences Of In-Service Teachers In Implementing Education For Sustainable Development

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The 2030 Agenda for Sustainable Development underscores the importance of education in achieving its goals, with Education for Sustainable Development (ESD) pivotal in fostering sustainability competences. This study investigates in-service teachers' self-efficacy, perceived pedagogical content knowledge (PCK), and willingness to implement ESD using the Professional Action Competence in ESD (PACesd) framework. A quantitative survey design was employed with 475 in-service teachers from primary, middle, and high schools. Descriptive and inferential statistics were conducted, including MANOVA, to examine differences across professional areas and education levels where in-service teachers work (primary, middle and high school). Results showed no significant differences in PACesd dimensions among professional areas. However, among education levels, primary school teachers consistently demonstrated higher self-efficacy, PCK, and willingness compared to their middle and high school counterparts, with high school teachers scoring the lowest. Statistically significant differences in self-efficacy and willingness were observed among education levels. Post hoc analysis revealed primary school teachers scored significantly higher in these dimensions compared to high school teachers. These findings underscore the challenges faced by secondary education teachers, attributed to rigid, subject-specific curricula that hinder interdisciplinary and holistic ESD approaches. The study calls for targeted professional development, curricular reforms, and strategies to boost teachers' willingness to implement ESD, as it emerged as the lowest-scoring dimension. Future research should explore strategies for integrating interdisciplinary approaches and overcoming barriers to ESD adoption across educational levels.

Keywords: sustainability, teacher education, secondary education

Introduction

The 2030 Agenda for Sustainable Development (SD), adopted by the UN in 2015, outlines 17 Sustainable Development Goals (SDGs) and 169 targets for achieving sustainability by 2030 (UN, 2015). Reaching these goals requires individuals with the knowledge, skills, and values to become sustainability change-makers. Education for Sustainable Development (ESD), emphasized in SDG Target 4.7, is key to equipping learners with the tools to promote SD, including sustainable lifestyles, human rights, gender equality, peace, cultural diversity, and global citizenship (Rieckmann, 2017; UN, 2015). ESD fosters competences for critical reflection on actions, promoting sustainable behaviours and active socio-political engagement (Rieckmann, 2017). Its goal is to develop knowledgeable, active citizens committed to sustainability (Biasutti et al., 2016; Carbach & Fischer, 2017). Teachers, essential to ESD implementation, must have the competences to develop action-competent learners (Isac et al., 2022).

Existing studies largely emphasize teachers' knowledge and self-efficacy regarding their competences in implementing ESD or environmental education (e.g., Gardner, 2009; Moseley et al., 2010), while willingness, a crucial competence component (Sass et al., 2022; Vukelić, 2022), is often overlooked. This study adopts the Professional Action Competence in ESD (PACesd) framework by Sass et al. (2022) which integrates self-efficacy, perceived pedagogical content knowledge (PCK), and willingness to implement ESD among primary and secondary in-service teachers. The framework's holistic approach that incorporates holism, pluralism, and action-orientedness makes it particularly relevant for exploring ESD competences in depth.

The literature shows fewer studies on in-service teachers' competences in ESD or environmental education compared to pre-service teachers (e.g., Effeney & Davis, 2013; Gardner, 2009; Saribas et al., 2014). Moreover, existing research predominantly involves primary school teachers (e.g., Effeney & Davis, 2013; Gardner, 2009). While primary school teachers often find it easier to integrate ESD into their teaching practices due to the flexibility of their curricula (Taylor et al., 2019), teachers at higher education levels frequently encounter challenges arising from subject-specific curricula that limit interdisciplinary approaches (Borg et al., 2012). This highlights the importance of including teachers from higher education levels in studies on ESD competences. Investigating how teachers at these levels are challenged in implementing ESD, particularly within the constraints of their subject areas, is crucial (Isac et al., 2022). Accordingly, this study aimed to explore potential differences in ESD competences among primary (1st to 4th grade), middle (5th to 8th grade) and high school (9th to 12th grade) in-service teachers, as well as differences based on the disciplinary areas in which they teach. The research questions are as follows:

- What are the levels of self-efficacy, perceived PCK, and willingness to implement ESD among in-service teachers?
- Are there statistically significant differences in teachers' professional action competence in ESD among in-service teachers from different disciplines?
- Are there statistically significant differences in teachers' professional action competence in ESD among in-service teachers teaching at different levels of education (i.e., primary, middle, and high school)?

Method

Research Design

This study employed a cross-sectional survey research design to explore differences in self-efficacy, perceived PCK, and willingness to implement ESD among primary, middle, and high school in-service teachers.

Participants

A total of 475 in-service teachers participated, with 64.4% female and 35.5% male. Most were primary school teachers (42.5%), followed by middle school teachers (35.8%), and high school teachers (21.7%).

Instrument

The study utilized the PACesd Scale, developed by Sass et al. (2022), to assess teachers' self-efficacy, perceived PCK, and willingness to implement ESD. The reliability analysis in the current study demonstrated excellent internal consistency (Cicchetti, 1994), with Cronbach's alpha values of 0.96 for self-efficacy regarding ESD, 0.98 for perceived PCK about ESD, and 0.97 for willingness to implement ESD.

Procedure

The PACesd data collection instrument was administered collectively to in-service teachers with the majority of participants completing the survey in approximately 10 minutes. Formal approval was obtained from the university's ethics committee prior to the start of the study. Participation was entirely voluntary and respondents were not required to provide their names or any other identifying information, ensuring anonymity.

Data Analysis

Both descriptive and inferential statistical analyses were conducted using SPSS 29. Descriptive statistics were employed to summarize and organize the study's data and to address the first research question. To address the second and third research questions, multivariate analysis of variance (MANOVA) was performed at a .05 alpha significance level. Before running the analysis, all necessary MANOVA assumptions were checked and fully met.

Results

The results of descriptive statistics are presented in Table 1. The maximum possible scores are 60 for self-efficacy, 66 for perceived PCK, and 60 for willingness. The total mean scores for the dimensions of PACesd are as follows: self-efficacy is 41.5, perceived PCK is 45.2, and willingness is 37.2. Additionally, among education levels, primary school teachers consistently scored higher than middle and high school teachers across three dimensions, with high school teachers having the lowest scores.

Table 1. Descriptive statistics.

Variable	*N*	*M* (Self-efficacy)	*SD*	*M* (perceived PCK)	*SD*	*M* (Willingness)	*SD*
Discipline							
Primary	203	42.8	11.0	46.3	13.2	38.7	12.4
Science	82	42.0	9.6	46.7	11.5	37.7	11.3
Social Sciences	45	42.4	8.9	45.2	12.8	37.5	12.5
Physics	23	42.2	9.3	41.7	11.4	33.0	12.5
Biology	25	37.8	9.4	43.3	12.2	34.4	9.6
Chemistry	25	37.3	9.2	38.7	12.4	34.1	10.5
Geography	24	36.7	9.3	44.2	10.8	34.0	11.7
Visual Arts	17	38.5	11.5	43.5	13.4	32.7	9.2
Technology and Design	31	40.7	15.6	44.5	17.4	38.5	15.3
Education Level							
Primary School	203	42.8	11.0	46.2	13.1	38.6	12.3
Middle School	170	41.5	11.0	45.5	13.2	37.6	12.5
High School	102	38.8	9.5	42.5	11.9	33.8	10.7
Total	475	41.5	10.7	45.2	13.0	37.2	12.1

A one-way between-groups MANOVA was conducted to examine differences in PACesd across professional areas. The dependent variables included self-efficacy, perceived PCK, and

willingness to implement ESD. The independent variable was in-service teachers' professional area. Preliminary assumption tests revealed no serious violations. Results showed a statistically significant difference among professional areas on the combined dependent variables, F(24, 1346) = 1.99, p = .003, Wilks' Lambda = .90, partial η^2 = .033. However, when analysing the dependent variables individually with a Bonferroni-adjusted alpha level of .017, no statistically significant differences were found as indicated in Table 2.

Table 2. MANOVA results.

Variable		Sum of Squares	*df*	Mean Square	F	Sig.	Partial Eta Squared
Discipline							
	Self-efficacy	1946.7	8	243.3	2.149	.030	.036
	PCK	1952.6	8	244.0	1.462	.169	.024
	Willingness	1972.5	8	246.6	1.692	.098	.028

A separate one-way between-groups MANOVA was performed to investigate differences in PACesd based on the educational levels where in-service teachers work (primary, middle and high school). The dependent variables were the same: self-efficacy, perceived PCK, and willingness to implement ESD. Preliminary assumption tests were satisfactory. A statistically significant difference was found among educational levels on the combined dependent variables, $F(6, 940) = 2.32$, $p = .031$, Wilks' Lambda = .97, partial η^2 = .015. As seen in Table 3, when considering the dependent variables separately with a Bonferroni-adjusted alpha level of .017, statistically significant differences were observed for self-efficacy scores, $F(2, 472) = 4.58$, $p = .011$, partial η^2 = .019. Post hoc analyses revealed that primary school teachers reported significantly higher self-efficacy scores ($M = 42.8$, $SD = 11.0$) compared to high school teachers ($M = 38.8$, $SD = 9.5$), $p = .007$. Significant differences were also found in willingness scores, $F(2, 472) = 5.52$, $p = .004$, partial η^2 = .023. Post hoc results indicated that primary school teachers ($M = 38.6$, $SD = 12.3$) reported significantly higher willingness scores than high school teachers ($M = 33.8$, $SD = 10.7$), $p = .003$. Middle school teachers ($M = 37.6$, $SD = 12.5$) also had significantly higher willingness scores than high school teachers ($M = 33.8$, $SD = 10.7$), $p = .033$.

Table 3. MANOVA results.

Variable		Sum of Squares	*df*	Mean Square	F	Sig.	Partial Eta Squared
Education Level							
	Self-efficacy	1042.3	2	521.1	4.583	.011	.019
	PCK	1002.7	2	501.4	3.006	.050	.013
	Willingness	1597.1	2	798.5	5.520	.004	.023

Conclusion And Discussion

This study has shown that although there were no statistically significant differences across professional areas in terms of self-efficacy, perceived PCK, and willingness to implement ESD, statistically significant differences were found across educational levels (primary, middle, and high school) in terms of self-efficacy regarding ESD and willingness to implement ESD. This study has demonstrated that primary education teachers tend to show higher self-efficacy,

perceived PCK, and willingness compared to their peers in secondary education, similar to the findings of Isac et al. (2022). Previous studies have reported that secondary education teachers often exhibit lower levels of commitment and higher feelings of inadequacy concerning the knowledge and skills required for the implementation of ESD (Borg et al., 2012; Popova et al., 2016; Taylor et al., 2019). As Isac et al. (2022) point out, in the literature, these perceptions are attributed to the structure of secondary education which emphasizes subject-specific knowledge and provides limited opportunities for teacher training. This organizational framework restricts the adoption of interdisciplinary and holistic approaches which are essential for developing competences in ESD. Besides these, the lowest mean score for willingness might suggest a gap between teachers' capabilities and their motivation to implement ESD, highlighting the need to enhance their commitment and engagement.

Implications And Future Work

The study highlights key implications and future directions. To improve secondary teachers' self-efficacy, PCK and willingness in ESD, targeted professional development and curricular reforms promoting interdisciplinary and holistic approaches are needed. Future research should identify strategies for integrating interdisciplinarity in secondary education, assess the long-term impact of ESD training, and explore barriers and enablers of ESD adoption across professional areas. Moreover, efforts should prioritize enhancing teachers' willingness to implement ESD, as it emerged as the dimension with the lowest mean score within PACesd.

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Global Citizenship Education As A Transformative Framework For Reorienting Education Systems Towards Community Needs And Sustainable Development

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Global Citizenship Education (GCE) is increasingly recognised as a transformative educational approach that equips learners with the knowledge, skills and values required to address complex global challenges such as climate change, inequality and sustainable development. Grounded in critical pedagogy, transformative learning and systems thinking, GCE challenges conventional education systems characterised by rigid curricula, standardised assessment and hierarchical pedagogies. This paper explores how GCE reorients education systems towards inclusivity, critical engagement and community relevance while supporting the achievement of the Sustainable Development Goals (SDGs), particularly Goals 4, 11 and 13. Using a qualitative, document-based multiple case study approach, the study analyses selected examples from Africa, Europe and Asia, including Ubuntu-inspired education initiatives in South Africa, the Global Learning Programme in the United Kingdom and Japan's Education for Sustainable Development initiatives, with specific reference to RCE Okayama. The findings demonstrate how GCE is enacted through participatory, context-responsive and interdisciplinary pedagogies that connect local realities with global concerns. While GCE holds significant transformative potential, the study identifies persistent challenges related to resistance to change, Western-centrism and assessment practices. The paper concludes by proposing strategies for strengthening the integration of GCE through teacher education, policy alignment, community engagement and the use of digital technologies.

Keywords: Global Citizenship Education, Transformative Learning, Sustainable Development Goals, Community-Responsive Education, Education Systems Transformation.

Introduction

Global Citizenship Education (GCE) has gained prominence in the 21st century as globalization intensifies interconnected challenges such as climate change, migration and inequality. Traditional education systems often fail to prepare learners to navigate these complexities. GCE bridges this gap by fostering global awareness, critical thinking and collective responsibility (Duarte & Robinson-Jones, 2022; Pacho, 2020). It emphasizes cognitive, socio-emotional and behavioural dimensions to enable learners to critically engage with pressing global issues (Sun, 2020). GCE aligns with SDGs, especially Goal 4 (quality education), Goal 11 (sustainable communities) and Goal 13 (climate action) (Khoo & Jørgensen, 2021; Stein, 2021). Its interdisciplinary framework equips learners to address global challenges while fostering local resilience and action.

Aim And Research Questions

This study aims to explore how Global Citizenship Education is conceptualised and implemented as a transformative framework within science and sustainability-oriented education systems and how it responds to community needs for sustainable development.

Research Questions:

1. How is Global Citizenship Education conceptualised as a transformative approach within contemporary education systems?
2. How are GCE principles enacted in selected case studies across Africa, Europe and Asia?
3. What pedagogical and contextual features characterise these GCE initiatives?
4. What challenges and opportunities emerge in implementing GCE in diverse educational contexts?
5. What implications do these cases offer for strengthening science education for sustainable development?

Current Educational Practices

Traditional education systems emphasize standardized testing, rigid curricula and rote learning, which often marginalize critical thinking, collaboration and adaptability. These systems frequently reflect Western-centric methodologies, sidelining Indigenous and local perspectives (Silva et al., 2023). GCE offers an alternative by promoting interdisciplinary learning, global interconnectedness, and active problem-solving. It shifts the focus from knowledge retention to critical engagement with real-world issues (Pacho, 2020). However, implementing GCE faces hurdles such as resistance from traditional systems, resource limitations and assessment challenges (Bamber et al., 2018).

Case Studies

The implementation of Global Citizenship Education (GCE) differs across cultural and geographical contexts, mirroring various local challenges and opportunities. Analysing case studies from Africa, Europe and Asia provides important perspectives into the integration of GCE concepts into global education systems, promoting global citizenship while considering local contexts. These examples demonstrate the versatility of GCE in building connection, critical Thinking And Sustainability Within Several Cultural Contexts.

Africa: Ubuntu Philosophy In Education

The Ubuntu philosophy, rooted in African traditions, emphasizes communal responsibility and interconnectedness. In South Africa, Ubuntu-inspired programs address social and environmental challenges by promoting collaboration and collective accountability (Sipondo, 2025). These programs connect local cultural heritage with global perspectives, fostering a sense of belonging and environmental care.

Europe: Global Learning Programme (UK)

The UK's Global Learning Programme (GLP) integrates GCE values through activities such as model United Nations debates and sustainability seminars. These initiatives enhance learners' understanding of global challenges while fostering critical thinking and empathy (Huckle, 2015). However, critics highlight challenges such as curriculum overload and resource constraints (Collado-Ruano, 2016).

Asia: Education For Sustainable Development (Japan)

Japan's Education for Sustainable Development (ESD) integrates GCE principles into formal education, emphasizing learner-centered methodologies such disaster preparedness and environmental conservation (Ferguson et al., 2022). Programs such as RCE Okayama demonstrate how contextualizing GCE within local circumstances can empower learners to address both local and global challenges. RCE Okayama (Regional Centre of Expertise on

Education for Sustainable Development) is part of a global network recognised by the United Nations University. It functions as a collaborative platform linking schools, universities, local government, civil society and communities to advance Education for Sustainable Development. In Japan, RCE Okayama exemplifies how GCE and ESD principles are embedded within local contexts through place-based learning, disaster preparedness education and environmental stewardship. Its inclusion in this study highlights the importance of community-driven, context-sensitive approaches to global citizenship education.

Methodology

This study adopts a scoping qualitative, exploratory research design grounded in an interpretivist paradigm, recognising that educational practices are socially constructed and context-dependent (Creswell & Creswell, 2018; Pervin & Mokhtar, 2022). The study is based on secondary data and does not involve primary data collection at this stage. A document-based multiple case study approach was employed to explore how Global Citizenship Education is implemented in different geographical and cultural contexts (Yin, 2009). The cases were purposively selected from Africa, Europe and Asia to illustrate different yet comparable applications of GCE within formal and non-formal education systems.

Selection Criteria For Case Studies Included:

- Explicit reference to Global Citizenship Education or Education for Sustainable Development
- Clear relevance to science, sustainability or environmental education
- Availability of sufficient peer-reviewed or institutional documentation
- Representation of different socio-cultural contexts

The literature reviewed comprised peer-reviewed journal articles, policy documents and programme reports sourced from databases including Google Scholar, JSTOR, Semantic Scholar and IEEE Xplore. Inclusion criteria focused on relevance to GCE, sustainability and educational transformation. The selected documents were analysed thematically to identify recurring patterns, challenges and pedagogical strategies related to GCE implementation (Bryman, 2016).

Discussion

This section explores the potential for change of Global Citizenship Education (GCE) as a paradigm for overcoming the shortcomings that plague traditional education systems. This presentation clarifies the benefits, challenges and solutions for enhancing Global Citizenship Education (GCE), demonstrating its capacity to provide learners with the requisite skills, information and values to adeptly go through a progressively interconnected and complicated world.

Benefits Of GCE Integration

Through the development of critical thinking, multicultural awareness and global responsibility, GCE equips learners to engage substantively with real-world challenges, including climate change, socioeconomic injustice and global health crises (Bamber et al., 2018; Pacho, 2020). Its focus on multidisciplinary and interactive learning connects education with global citizenship, guaranteeing that learning aligns with society demands. GCE supports diversity by including multiple cultural perspectives and knowledge frameworks, especially those of Indigenous and underprivileged populations. This inclusive methodology facilitates learning and guarantees that education mirrors the actual experiences of numerous communities, promoting empathy, solidarity and an understanding of global interdependence (Dreamson, 2018; Smith, 2018). To

attain genuine inclusion, GCE must transcend its dependence on Western epistemologies by integrating non-Western and Indigenous perspectives as equal contributors to its evolution (Dreamson, 2018). This strategy is consistent with coeducation principles, encouraging intercultural involvement and overcoming gaps in access to and quality of education worldwide (Ainscow, 2020).

An interdisciplinary approach to Global Citizenship Education amplifies its transformative capacity by addressing global systems of oppression and domination. Analytical categories such race, gender and class are employed to enhance learners' consciousness of their collective responsibility and culpability in these frameworks, thereby promoting political engagement and social justice outcomes (de Vries, 2020). This fundamental aspect of GCE corresponds with Freirean pedagogy, emphasising critical thinking, self-reflection and praxis as the basis for transformational action (Tarozzi & Inguaggiato, 2018). Ultimately, GCE improves learners' capacity for critical thinking and collaborative action, critical competencies for solving complicated global challenges demanding coordinated, interdisciplinary approaches. By emphasising active participation rather than passive knowledge absorption, GCE enables learners to become proactive problem-solvers and proponents of sustainable development (Khoo & Jørgensen, 2021; Santamaría-Cárdaba et al., 2021). Teacher education programs serve as crucial in this process, focussing on transformational methodologies that equip teachers to motivate and direct learners towards these objectives.

Challenges In Implementation

Although its revolutionary commitment, Global Citizenship Education (GCE) encounters major challenges in implementation across various contexts. A major challenge is the opposition from stakeholders established in traditional educational systems, such as policymakers, teachers and organisations that emphasise standardised testing and inflexible curricula. These systems frequently exhibit insufficient flexibility to support the transdisciplinary and participative nature of GCE, resulting in conflicts between traditional practices and transformational educational objectives. To overcome this opposition, systemic adjustments that emphasise innovation and adaptation are necessary.

A major challenge is the perception of GCE as Western-centric, especially given that its concepts and approaches are primarily sourced from Global North contexts. This perspective diminishes its significance and acceptance in various cultural contexts (Lauwerier, 2020; Akkari & Maleq, 2020). In West Africa, the external roots of GCE and inadequate local stakeholder engagement reduce its applicability (Lauwerier, 2020). Furthermore, South Korean teachers face challenges stemming from neoliberal and post-colonial proposals that marginalise Global Citizenship Education within the curriculum (Kim, 2019). Asian colleges experience supplementary barriers including financial constraints, inflexible curricula and challenges in maintaining cultural relevance (Sain et al., 2025). These examples emphasise the necessity for localised and context-specific strategies that integrate indigenous knowledge systems and culturally relevant behaviours (Ydo, 2023). The contested nature of GCE further hampers its execution. Various conceptions of global citizenship exist, frequently shaped by different cultural and ideological contexts (Akkari & Maleq, 2020). Certain teachers perceive GCE as a neocolonial construct, however others contend it may be adapted to address local challenges via customised strategies (Parejo et al., 2022). To maintain GCE's relevance and influence, it must acknowledge local contexts and question its dependence on Western frameworks.

Strategies For Improvement

To address the challenges of implementing Global Citizenship Education (GCE) and fully utilise its revolutionary potential, many measures must be prioritised. Integrating GCE activities with broader global targets, specifically the Sustainable Development Goals (SDGs), especially SDG 4.7, guarantees consistency and expandability (Abazov, 2021; Longueira Matos & Vela-Eiden, 2020). Programs such as Bridge 47 reflect the value of collaborative efforts in advancing Global Citizenship Education and championing educational changes aimed at social transformation (Longueira Matos & Vela-Eiden, 2020). Policymakers must devise context-specific policies and nurture collaborations across governments, non-governmental organisations and educational institutions to overcome structural challenges especially for marginalised populations (Akkari & Maleq, 2020; Vindigni, 2024). Ongoing assessment and modification of policies is required to maintain relevance in changing global environments (Vindigni, 2024). Professional development programs must prioritise interdisciplinary learning, cultural proficiency and creative pedagogical approaches consistent with Global Citizenship Education concepts (Parejo et al., 2022). Effective professional development integrates experiential learning, critical thinking and chances for reflection and practice, addressing intellectual, affective and action-oriented domains (Darling-Hammond et al., 2017).

Technology plays an important role in broadening access to GCE and augmenting its effectiveness. Digital exchanges, digital tools and online resources facilitate worldwide collaboration and mutual understanding, producing holistic and interactive learning experiences that surpass geographical limitations (Abimbola Eden et al., 2024). Academic literacy facilitators can employ multimodal literacies, such as digital discourses, to successfully communicate GCE principles (Eybers & Muller, 2023). Teachers must synchronise technological tools with instructional objectives, promote digital literacy and stimulate critical thinking to optimise technology's positive impact (Abimbola Eden et al., 2024). These strategies facilitate the creation of more inclusive, egalitarian and sustainable learning environments that equip learners to confront the complicated issues of a connected world.

Conclusion

Global Citizenship Education represents a transformative shift in education. Along fostering critical thinking, global awareness and inclusive practices, GCE prepares learners to navigate and address the complexities of a globalized world. Despite challenges, its potential to create sustainable and equitable education systems underscores its importance.

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Assessing Students' Sense Of Responsibility In Chemistry Education: Development And Validation Of An STSE-Based Instrument

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Developing students' sense of responsibility is a central goal of contemporary science education, particularly in addressing Science–Technology–Society–Environment (STSE) issues. However, empirical tools for assessing students' responsibility in discipline-specific contexts remain limited. This study aimed to develop and validate an assessment tool for measuring the sense of responsibility among students in grades 9–12 within chemistry-related STSE contexts. A scale development and validation design was adopted. The assessment tool was constructed around three authentic chemistry contexts—hand warmers, global warming, and soda-making—selected for their curricular relevance and real-life significance. Based on a theoretical framework, students' sense of responsibility was operationalized into three dimensions: personal responsibility, social responsibility, and scientific responsibility. Items were developed using a storyline-based approach and refined through student interviews and expert review. The instrument was administered to 2,366 students, and its psychometric properties were examined using a Multidimensional Rasch Model. The results indicated satisfactory reliability, with Expected A Posteriori/Plausible Value (EAP/PV) coefficients ranging from 0.63 to 0.76. Item fit statistics (infit and outfit MNSQ) fell within the acceptable range, supporting the structural validity of the instrument. Students demonstrated the highest levels of performance in social responsibility, followed by scientific and personal responsibility. Furthermore, students' attitudes toward science and STSE issues, as well as their understanding of the nature of science, were positively associated with responsibility, whereas academic achievement alone showed a weaker relationship. This study provides a validated, context-based instrument for assessing students' sense of responsibility in chemistry education. The findings highlight the importance of integrating STSE issues into chemistry curricula to support students' ethical reasoning, decision-making, and engagement with real-world scientific challenges. The assessment tool offers practical value for both research and instructional design and contributes to ongoing discussions on responsibility-oriented science education.

Keywords: Sense of responsibility; Chemistry education; Instrument development; Multidimensional Rasch model

Introduction

One of the visions of science education is to nurture scientifically literate students who can make informed decisions and take responsible actions in their lives (Sjöström & Eilks, 2018). As future citizens, students will inevitably face modern scientific issues such as climate change, collectively referred to as science-technology-society-environment (STSE) issues (Kruse et al., 2024). To prepare students for citizen engagement, increasing their sense of responsibility is an effective approach for addressing STSE challenges (OECD, 2018). Adolescence can now be seen as a time of opportunity for developing a sense of responsibility. Science education can foster students' sense of responsibility, enabling them to apply their understanding of scientific concepts and processes to issues that affect their lives, culture, and the environment as a means of caring for themselves, others, and their community. It encourages them to take a critical stance towards the products of science and technology while empowering them to reduce potential harm these products may have on individuals, societies, and environments (Onwu, 2017). Previous research has indicated that various methods, including science identity, environmental identity, and citizen

engagement, can be employed to assess the capacity for taking responsibility (Louros, 2022). However, there is little research focusing on identifying the most effective approach to evaluate students' capacity for taking responsibility. In this study, we designed an assessment tool to evaluate the attitudes and sense of responsibility of students in grades 9-12 when dealing with STSE issues. In addition, we investigated the relationship between scientific knowledge, nature of science, attitudes, academic performance, teacher support, school resources, and students' sense of responsibility.

Theoretical Framework

The Concept Of Take Responsibility

Science is a social enterprise that interacts with society in complex ways (Intemann & de MeloMartin,2010). Science should be described as a human activity that acknowledges the strengths of science and technology but also recognizes their limitations. In the specific topic we are discussing, we have the responsibility to ensure the conservation of resources, and to make students aware that we are accountable to society and will not destroy the environment. In science education, students should be encouraged to adopt a “critical thinking disposition” that allows them to investigate the pros and cons of any scientific and technological developments using their intellectual and ethical skills (Fuchs & Tan, 2022).

Existing literature categorizes responsibility into three types: personal responsibility, social responsibility, and scientific responsibility. Personal responsibility primarily revolves around individual consumption habits and lifestyle choices (Aygun et al., 2024; Louros, 2022). Social responsibility aims to promote social development and environmental conservation goals, involving the analysis, judgment, prediction, regulation, and decision-making of real-world issues in social contexts, including responsibilities for social development and environmental protection (Politi, 2024). Scientific responsibility is focused on advancing social development and reducing the negative impacts of science, encompassing scientific ethical responsibility and responsibility for the development of science (De Melo-MartíN & Intemann, 2023).

The capacity to take responsibility involves considering the future consequences of one’s actions, evaluating risks and rewards, and accepting accountability for one’s work. A performance of take responsibility is a person can reflect upon and evaluate his or her actions from the view of personal and societal goals. Acting ethically implies asking questions related to norms, values, meanings and limits, such as: What should I do? Was I right to do that? Where are the limits? Knowing the consequences of what I did, should I have done it? (OECD, 2018)

Assessing The Capacity Of Responsibility

Developing instruments to assess social responsibility is a complex process that requires careful consideration of cultural, ethical, and contextual factors. One notable example is the work by Dürten Röhm and Marissa Rollnick (2010), who developed an instrument to assess science students' views on the social responsibility of scientists. Their approach was based on the Views on Science-Technology-Society (VOSTS) instrument, which was originally designed to measure students' cognitive views on the interaction between science, technology, and society. The adapted instrument included multiple phases: interviews, open-response questionnaires, and fixed-response questionnaires. These methods were used to capture a comprehensive understanding of students' perspectives.

The development of social responsibility assessment tools typically involves both qualitative and quantitative methodologies. Qualitative methods, such as interviews and focus groups, are essential for capturing nuanced views and opinions. For example, Röhm and Rollnick used group

interviews and open-response questionnaires to gather initial data, which were then analysed to identify key themes and dimensions related to social responsibility. This iterative process allowed the researchers to develop a structured questionnaire that reflected the authentic views of the target population.

Quantitative methods, such as fixed-response questionnaires, are used to validate and generalize the findings. The final instrument developed by Röhm and Rollnick included 20 statements with multiple-choice options, allowing for statistical analysis of responses. This approach ensures that the instrument can be used across larger populations while maintaining reliability and validity (González-García et al., 2019).

Factors Affecting The Capacity Of Take Responsibility

Previous research suggests that a lack of understanding of science content hinders one's ability to negotiate STSE issues (Fowler & Zeidler, 2016). Knowledge is the primary influencing factor. According to the Knowledge-Attitude-Behaviour (KAP) model, knowledge influences attitudes, which in turn affect behavioural awareness. Zoller (2013) argues that the "translation" of science and technology into actions that are responsible to society and technology depends on what the relevant personnel believe and what attitudes they hold when facing problems to be solved. Therefore, attitudes towards science and STSE issues are also important influencing factors. Understanding the nature of science helps students grasp what science is and how it works. Existing studies have shown that the nature of science enables students to be open-minded about scientific knowledge and STSE issues, rather than accepting them blindly (Abd-El-Khalick, 2013). The nature of science is an influential factor that cannot be ignored (González-García et al., 2019). In addition to this, factors such as students' academic achievement, the attitudes of teachers and parents, and other elements can also influence students' sense of responsibility.

Research Questions

In this study, we designed an assessment tool to evaluate sense of responsibility of students in grades 9-12 when dealing with STSE issues. Additionally, we investigated the relationships between scientific knowledge, the nature of science, attitudes, academic performance, the attitudes of teachers and parents, school resources, and students' sense of responsibility.

RQ-1：How can an assessment tool of students' sense of responsibility be developed within a chemistry context?

RQ-2: What are the relationships between scientific knowledge, the nature of science, attitudes, academic performance, the attitudes of teachers and parents, school resources, and students' sense of responsibility?

Research Method And Design

Study Design

This study adopted a scale development and validation design to construct an assessment tool measuring students' sense of responsibility within chemistry-related Science–Technology–Society–Environment (STSE) contexts. A mixed-methods approach was employed, combining qualitative data from student interviews with quantitative data from large-scale questionnaire administration, to ensure both content validity and psychometric robustness of the instrument.

Development Of The Responsibility Assessment Tool

This study independently designed an evaluation tool to assess students' sense of responsibility in chemistry-related STSE contexts. The development process followed three sequential stages: (1) contextual selection and framework construction, (2) item development and expert validation,

and (3) large-scale pilot testing and psychometric analysis.

Context Selection And Framework Construction

The development of a social responsibility assessment tool specific to a chemistry context requires the selection of appropriate chemistry topics and the creation of authentic scenarios that can elicit students' responsibility-related reasoning. Through curriculum analysis aligned with national chemistry standards, three chemistry contexts were purposively selected: the chemistry of hand warmers, global warming, and the soda-making process.

These contexts were chosen because they involve core chemical principles familiar to students in grades 9–12, thereby minimizing cognitive load while maximizing opportunities for responsibility-related decision-making. The chemistry of hand warmers illustrates the application of oxidation reactions in daily life and highlights scientific responsibility for consumer safety. Global warming draws on energy-related chemical knowledge and emphasizes chemistry's role in addressing global environmental challenges. The soda-making process involves industrial chemistry and wastewater treatment, requiring students to balance economic efficiency with environmental protection and social responsibility.

Based on the theoretical framework, students' sense of responsibility was operationalized into three dimensions: personal responsibility, social responsibility, and scientific responsibility. Each dimension reflects progressively complex forms of responsibility, ranging from individual behavioural choices to collective decision-making and scientific innovation.

Item Development And Validation

The assessment tool was designed using a storyline-based approach, in which each chemistry context served as a coherent narrative stimulus embedding multiple decision points. As each storyline unfolded, 10–15 items were embedded within each context, resulting in a total of 30–45 items across the three responsibility dimensions.

Each item consisted of a multiple-choice question with four response options, representing increasing levels of responsibility. Responses were scored on an ordinal scale from 1 to 4, with higher scores indicating a higher level of responsibility.

To ensure content validity, extensive semi-structured interviews were conducted with students prior to item construction. Students were asked to explain how they would respond to each scenario and why. Their authentic responses were coded and used as the basis for constructing realistic and developmentally appropriate response options.

The initial item pool was reviewed and refined by two experts in chemistry education research and one Ph.D. researcher in chemistry education, focusing on clarity, relevance, and alignment with the intended responsibility dimension. Revisions were made iteratively until consensus was reached on item appropriateness and representativeness.

An example item from the assessment tool is presented below to illustrate the scoring logic and responsibility progression:

Consumers have reported that some heat packs may become too hot, posing a risk of burns. How do you think the research team should best respond? ( )

A. I would like to adjust the thickness of the heat pack packaging to prevent consumers from feeling it is too hot. (1 point)

B. I would like to analyse the cause of overheating and improve the heating mechanism to ensure it stays within a safe range. (3 points)

C. I would like to provide more guidance on preventing burns to help consumers use the heat packs safely. (2 points)

D. I would like to develop heat packs with a temperature regulation function that can automatically adjust the heating temperature to ensure safety. (4 points)

Assessment Of Influencing Factors

In addition to the responsibility assessment tool, a separate questionnaire was developed to measure factors potentially influencing students' sense of responsibility, including attitudes towards science, attitudes towards STSE issues, understanding of the nature of science, academic achievement, teachers' and parents' attitudes, and school resources.

This instrument was adapted from established scales reported in previous research (Hillman et al., 2016) and consisted of 30 Likert-scale items rated on a five-point scale ranging from "strongly disagree" to "strongly agree." Higher scores indicated more positive attitudes or greater perceived support.

Participants And Data Collection

A total of 2,366 students in grades 9–12 participated in the study. Among them, 44.4% were female and 55.6% were male. Data were collected through a 40-minute online assessment, administered during regular school hours.

Following the quantitative assessment, 10 students were purposively selected for follow-up semi-structured interviews, each lasting approximately 30 minutes, to explore students' perceptions of the assessment tool and their engagement with the chemistry contexts.

Ethical approval for the study was obtained from the relevant institutional review board. Informed consent was obtained from all participating students and their guardians prior to data collection, and all responses were anonymized to ensure confidentiality.

Data Analysis

To examine the psychometric properties of the responsibility assessment tool, a Multidimensional Rasch Model (a form of Multidimensional Item Response Theory, MIRT) was applied. This model allows for the simultaneous estimation of item difficulty and student ability across multiple latent dimensions while accounting for the interrelationships among dimensions.

The analysis was conducted using ConQuest Version 2.0 software, which is suitable for large-scale educational assessments. Model fit was evaluated using infit and outfit mean square (MNSQ) statistics, with acceptable values ranging from 0.7 to 1.3. Reliability was assessed using Expected

A Posteriori/Plausible Value (EAP/PV) Reliability Coefficients

To address Research Question 2, correlation and regression analyses were conducted to examine the relationships between students' sense of responsibility and influencing factors, including scientific knowledge, nature of science, attitudes, academic achievement, and perceived support from teachers, parents, and schools.

Findings

Psychometric Properties Of The Responsibility Assessment Tool

The psychometric quality of the responsibility assessment tool was examined using a multidimensional Rasch model. Overall, the model demonstrated satisfactory fit and reliability,

indicating that the instrument was appropriate for measuring students' sense of responsibility across multiple dimensions.

The reliability coefficients (eap/pv), which indicate the stability and internal consistency of the measurement, ranged from 0.63 to 0.76 across the three dimensions of responsibility, suggesting acceptable reliability for an educational assessment tool. Specifically, social responsibility showed the highest reliability, followed by scientific responsibility and personal responsibility.

Item fit statistics further supported the adequacy of the model. Both infit and outfit mean square (mnsq) values for all items fell within the acceptable range of 0.7 to 1.3, indicating that the observed student responses were consistent with the expectations of the Rasch model and that no items exhibited substantial misfit.

These results provide evidence for the structural validity of the assessment tool and support the multidimensional conceptualization of students' sense of responsibility in chemistry-related stse contexts.

Differences Across Responsibility Dimensions

Analysis of students' performance across the three responsibility dimensions revealed statistically meaningful differences. Students demonstrated the highest levels of performance in social responsibility, followed by scientific responsibility, while personal responsibility scores were comparatively lower.

The consistently higher scores in social responsibility suggest that students are more inclined to recognize collective obligations and societal consequences of chemistry-related issues than to reflect on personal behavioural changes or engage in innovation-oriented scientific responsibility. No significant differences were observed across demographic variables in other dimensions.

Relationships Between Responsibility And Influencing Factors

To address Research Question 2, the relationships between students' sense of responsibility and influencing factors—including scientific knowledge, understanding of the nature of science, attitudes toward science and STSE issues, academic achievement, and perceived support from teachers, parents, and school resources—were examined.

The findings indicated that students' attitudes toward science and STSE issues were significantly associated with higher levels of responsibility, particularly in the social responsibility dimension. Understanding of the nature of science also showed a positive relationship with scientific responsibility, suggesting that students who possessed a more informed view of how science operates were more likely to engage in ethically and socially responsible reasoning.

In contrast, academic achievement alone did not emerge as a strong predictor of responsibility, indicating that responsibility-related competencies extend beyond traditional measures of academic performance. Perceived support from teachers and schools showed a moderate association with responsibility, highlighting the role of the educational environment in shaping students' responsibility-related attitudes.

Student Perceptions Of The Assessment Tool

Qualitative data from follow-up interviews provided complementary insights into students' experiences with the assessment. Participants reported that the assessment scenarios were engaging and closely connected to real-life situations, which increased their motivation to think deeply about the issues presented.

Several students noted that even when their chemistry grades were not strong, they felt capable of applying chemical knowledge to socially meaningful problems. This sense of relevance and

usefulness contributed to a feeling of accomplishment and value, suggesting that the assessment tool successfully elicited responsibility-related engagement beyond rote knowledge recall.

Discussion And Implications

Interpretation Of Findings

This study aimed to develop and validate an assessment tool for measuring students' sense of responsibility within chemistry-related STSE contexts. The findings provide empirical support for conceptualizing responsibility as a multidimensional construct comprising personal, social, and scientific dimensions, consistent with prior theoretical frameworks (OECD, 2018; De Melo-Martín & Intemann, 2023).

The higher levels of social responsibility observed among students may reflect the increasing emphasis on collective action and societal challenges, such as climate change, within contemporary science education and public discourse. In contrast, scientific responsibility—which involves innovation, ethical reflection, and long-term technological decision-making—may require more explicit instructional support to develop fully in secondary education contexts.

The significant relationships between responsibility and attitudes toward science and STSE issues underscore the importance of affective and epistemic dimensions in responsibility development. These findings align with the Knowledge–Attitude–Behaviour (KAB) framework, suggesting that responsibility is not solely driven by content knowledge but is strongly shaped by students' values, beliefs, and perceptions of science's role in society.

Educational Implications

The validated assessment tool developed in this study offers several implications for chemistry education. First, it provides educators and researchers with a practical instrument for diagnosing students' responsibility-related competencies in authentic STSE contexts. Such diagnostic information can support curriculum design that intentionally integrates responsibility development alongside conceptual understanding.

Second, the findings suggest that embedding chemistry instruction within meaningful socio-scientific scenarios can enhance students' engagement and sense of purpose, particularly for students who may not excel in traditional academic assessments. This highlights the potential of STSE-based instruction to promote educational equity by valuing diverse forms of competence beyond test scores.

Third, the observed influence of teacher and school support emphasizes the need for learning environments that encourage discussion, reflection, and ethical reasoning. Professional development for teachers should therefore focus not only on content delivery but also on facilitating dialogue around responsibility, ethics, and societal implications of chemistry.

Limitations And Future Research

Several limitations of this study should be acknowledged. First, although the sample size was large, the participants were drawn from a limited educational context, which may constrain the generalizability of the findings to other regions or educational systems. Second, the assessment relied primarily on self-reported responses to hypothetical scenarios, which may not fully capture students' actual behaviour in real-world situations.

Third, while the Multidimensional Rasch Model provided strong evidence for structural validity, future studies could further examine the external validity of the instrument by comparing responsibility scores with observed behaviours or longitudinal outcomes.

Future research should explore how students' sense of responsibility develops over time and how

different instructional interventions influence each responsibility dimension. Cross-cultural validation of the assessment tool would also be valuable to examine how responsibility in chemistry is shaped by cultural, social, and educational contexts.

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From Instrumental To Communicative Rationality: Reimagining Science Education For Sustainability In Socio-Political Conflicts

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We present the early stages of an interdisciplinary research aimed at promoting future-oriented agency competencies to support upper secondary school students in participating in the public debate on the energy transition within their communities. As a case study, the research focuses on Sardinia (Italy), where renewable energy policies have triggered strong social tensions: while national energy policies assign a strategic role in Italy's decarbonization efforts to the island's renewable energy capacity, local activists denounce renewable energy projects as speculative ventures, with severe impacts on landscapes and land ownership. This research is structured in three phases. The first step was ethnographic fieldwork, focusing on the social movement that opposes new energy infrastructures, addressing its historical, cultural, and economic background. As a second step, we will adapt an MGA (Modelling to Generate Alternatives) energy-system model as a tool for enabling students to understand the complexity of the energy transition and to critically explore alternative energy scenarios. Finally, we will test the developed educational tools directly in the schools of the communities involved in the study. As a preliminary conclusion, we propose to interpret the tensions between the local communities' lifeworld and the development of new energy infrastructures as a conflict between communicative rationality and instrumental rationality, according to Habermas' theory of communicative action. From this perspective, the use of an MGA energy-system model within an interdisciplinary education framework appears as an attempt to rethink science education for sustainability in line with the ideal of communicative rationality.

Keywords: sustainability, communicative rationality, future-oriented science education.

Premise

In line with the Paris Agreement of 2015, the European Union aims to reach climate neutrality by 2050 through an ambitious energy transition program known as the European Green Deal. The objective of climate neutrality by 2050 became legally binding in 2021 with the adoption of the European Climate Law and the legislative package Fit for 55, which sets the intermediate target of a 55% reduction in greenhouse gas emissions by 2030.

Although the European Green Deal formally claims to reconcile environmental sustainability, economic growth, and social cohesion (European Commission, 2018), the energy transition has generated significant social tensions (Eichenauer & Gailing, 2022; Sovacool et al., 2022). European energy policies operate within a neoliberal framework (Laes & Bombaerts, 2022), as evidenced by the use of market-based instruments such as the Emissions Trading System (ETS) (Verbruggen et al., 2019). Within this framework, procurement procedures that favor large-scale capital over local actors can contribute to strong power asymmetries in electricity system governance (Kirkegaard et al., 2021). Especially in Southern Europe, a predominantly top-down approach to energy governance, characterized by massive investments in large-scale power plants and limited engagement of local communities, has triggered widespread social opposition to the energy transition (Osti, 2018; Wolsink, 2007). In Italy, energy policies have been marked by pronounced inequalities in the distribution of the costs and benefits of the transition (Albulut, 2026). These social tensions have been further exacerbated by the significant acceleration of the energy transition promoted under the RePowerEU plan in 2022 (Pavlenko, 2025), particularly as a result of land grabbing associated with the expansion of wind farms.

In the coming years, tensions between local communities and renewable energy projects are expected to increase due to upcoming commitments to the transition.

Research Question

According to the social science literature, the engagement of local communities in decision-making processes is effective in supporting the development of energy policies with broader social support, thereby reducing social opposition to renewable energy facilities (Wolsink, 2007). Our research aims to explore the potential role of schools, as sites of science education and critical citizenship, to increase the capacity of local communities to participate in public debate in an informed and effective way, in contexts where energy policies have already triggered social opposition. In this context, a key question is whether science education for sustainability, by equipping high school students with future-oriented agency competences, can foster their participation in the decision-making processes – thereby contributing to identifying just transition policies supported by broader social consensus.

From this perspective, science education for sustainability cannot be reduced to simply explaining the rationale for – and advocating the urgency of – decarbonization, without criticizing the power asymmetries implicit in current energy policies. This is especially true in a context where public education was long used as a tool of cultural colonization, enforced assimilation, and eradication of local languages (Bandinu et al., 2003; Sorge, 2015). Rather than dismissing local movements' concerns by labelling them as irrational and excluding them from public debate – a rhetoric aimed at legitimizing asymmetric access to decision-making spaces in many conflicts over the appropriation of resources – this research aims to develop educational practices and tools that create space for polyphonic dialogue, recognizing the legitimacy of these voices.

Case Study

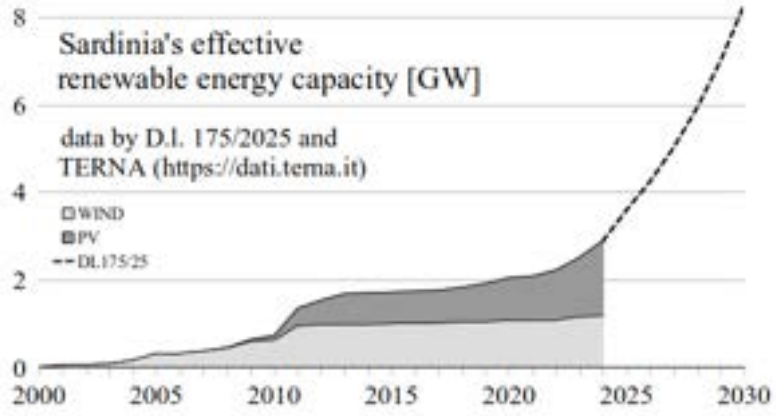
This research focuses on social tensions triggered by renewable energy policies in Sardinia (Italy). Sardinia, the second largest island in the Mediterranean, has a distinctive cultural identity and strong territorial rootedness. It is recognized as a highly suitable territory for renewable energy development (Politecnico di Milano, RELab, 2020), not only because of consistent wind patterns and high solar exposure, but also due to extensive grassland areas with little human presence. The most recent legislation (D.l.175/2025) establishes the target of 8.3 GW of effective renewable energy capacity in the region by 2030 as legally binding. At the beginning of 2023, it amounted to 2.5 GW. By late 2024, Italy's grid management company had received authorization applications exceeding 50 GW in Sardinia alone, against a national target of about 70 GW (TERNA, 2023a, 2023b, n.d.).

Since 2023, an increasing number of local committees have emerged in response to the surge in permit applications for wind and photovoltaic projects, denouncing this as a speculative strategy. Protests peaked between the summer and autumn of 2024, culminating both in a broadly supported citizens' initiative bill against new energy infrastructures and in a jurisdictional conflict between regional and national authorities over the allocation of decision-making authority (ANSA, 2024a, 2024b).

Structure Of The Research

The research unfolds in three phases. The first phase involved ethnographic fieldwork focused on the social movement opposing new energy infrastructures. The second phase will be devoted to developing educational tools to engage students in the public debate on the energy transition. The final phase will consist of implementing and evaluating these educational tools directly in the schools of the communities involved in the study.

Figure 1. Sardinia's effective renewable energy capacity.



Fieldwork

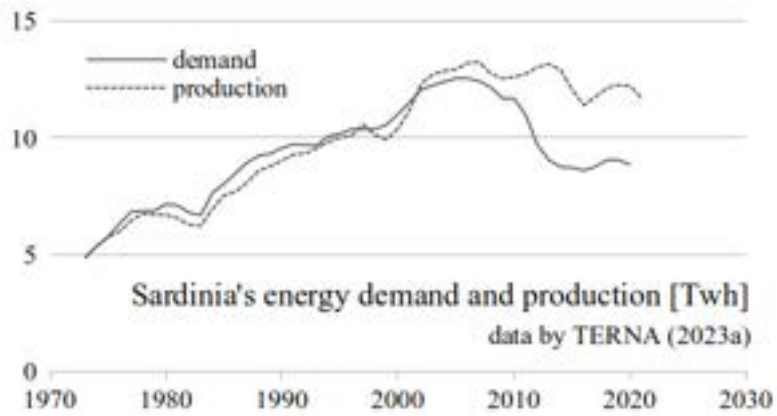
The first step of the research consists of ethnographic fieldwork on social opposition to energy policies. The aim of this inquiry is to provide a qualitative description of these tensions – with attention to the historical, cultural, and economic drivers of the opposition – so that these findings can be brought back to students through interdisciplinary teaching activities.

The fieldwork took place during 2025, over ten months. It was conducted using standard ethnographic methods, primarily participant observation and qualitative interviews. We conducted more than 40 hours of interviews with activists against *energy speculation* (using the movement's own definition), climate activists, teachers, local administrators, and journalists. Interviews followed an open-ended approach, starting from the central theme of the movement and concluding on the role and possibilities of younger generations in the decision-making process. Where possible, interviews were recorded. Conversely, when recording was likely to generate mistrust between the researcher and informants, conversations were summarized in field notes. We also conducted participant observation during street demonstrations and public assemblies, visited various energy infrastructures, and analysed local press and social media communication.

The movement is characterized by the demographic predominance of older adults. It is politically heterogeneous and has gained broad social support, without ideological cohesion but unified by a strong demand for self-determination – and specifically for self-determination in Sardinian energy policies. Criticism is related to a conflict over resources: land as a resource disputed between local farmers and external energy enterprises; similarly, the need to protect landscape and cultural heritage as resources for tourism; and the export of locally generated energy, judged as not sufficiently compensated by essential state services and compensatory schemes. But it goes well beyond this, involving deep symbolic factors tied to Sardinia's historical subordination to the central state, which long acted as a colonial force on the island.

For these reasons, decarbonisation policies are denounced by broad segments of the population as a new form of extractivism – one that, in Sardinia, has left a legacy of environmental degradation, public health issues, slow economic development, and demographic decline (Sorge, 2015). It is not only about the expropriation of material resources: the systematic exclusion of local communities from decision-making processes erodes spaces for dialogic debate and, in turn, leads to the collective expropriation of future-oriented agency, exacerbating social opposition.

Figure 2. Sardinia's energy demand and production.



Theoretical Framework

To support the design of the educational tools, we propose a framework grounded in Horkheimer's critique of instrumental rationality (1947/1974) and its further elaboration in Habermas's theory of communicative action (1981/1984).

In archaic Greece, a society marked by a strict hierarchy, myth held authoritative power over truth. When collective participation in the life of the polis expanded, driven by an emerging bourgeois class, new linguistic practices became necessary. The term logos – which in Homer still denoted a beguiling tale – now came to mean the common ground of discourse, where citizens could voice their demands and deliberate in pursuit of the common good, recognizing their shared belonging to the polis. Throughout its development, philosophical reflection tried to clarify the criteria for good argumentation, a process which culminated in the development of formal logic (Perelman, 2010). This can be understood as a calculative system aimed at determining an argument's validity, so as to arrive – at least ideally – at a unique conclusion to the debate, thereby closing the common ground of discourse.

As Horkheimer observes (1947/1974), when reason is reduced to mere calculation, it ceases to deliberate purposes – evaluating their legitimacy or desirability – and simply focuses on selecting the most efficient means to achieve them. It becomes instrumental rationality, aimed at pursuing goals withdrawn from public debate. Under this perspective, scientific knowledge, rather than guiding social actions toward shared values, offers legitimacy to a technocratic society where democratic dialogue loses influence on social life – a condition that can fuel violent reactions by groups excluded from decision-making processes.

Habermas (1981/1984), building on the early Frankfurt School's critique yet moving beyond it, reworks the notion of rationality into an explicitly communicative framework. Alongside purpose-oriented rational action (instrumental or strategic), he introduces the concept of communicative rational action, defined as linguistic practices aimed at mutual understanding. According to Habermas, the central conflict in contemporary society is no longer the class struggle but the conflict between instrumental rationality and communicative rationality, that is, the tendency of systemic rationality to colonize the communicative actions of a community, which he terms the lifeworld (adopting Husserl's terminology).

Instrumental And Communicative Rationality In Science Education

We propose to interpret the tensions between local communities and the development of new energy infrastructures as a conflict between communicative rationality and instrumental

rationality. If we accept this interpretation, it has significant implications for the design of teaching activities.

A science education entirely limited to instrumental rationality necessarily excludes students from any reflection on purposes, allowing only the calculation of efficient means to achieve predetermined goals as legitimate educational practice. Nevertheless, teleological reflection – such as critical inquiry into future scenarios – is essential to cultivate a future-oriented agency, which in turn is a prerequisite for addressing the current global crisis (Laherto & Rasa, 2022). Moreover, such an approach can degenerate into a form of strategic action, treating students as means to predefined ends – for example, the promotion of a specific energy policy. Thus, the same tensions driving social conflict may manifest within the school community, resulting in a biased rejection of scientific discourse.

We therefore ask whether science education practices can be oriented toward the ideal of communicative rationality, useful for deliberating on ends and not only for calculating more efficient means. We will explore this line of research by providing educators with tools to represent the complexity of the social issues involved in the conflict.

Future Steps

Engaging local communities in decision-making remains challenging, as it requires not only public spaces for collective deliberation, but also analytical tools accessible to non-specialists to evaluate alternative transition pathways. The next stage of the research will involve developing a computational model, adapted for educational use, to represent the range of possible decarbonization pathways available to policymakers.

Previous work has shown that the use of complex systems simulations in educational contexts can enable students to critically explore alternative future scenarios (Barelli, 2022; Fabbri, 2021; Miani, 2025). Building on this line of research but seeking specific tools to address issues related to the low-carbon transition, we have focused on a particular type of energy system model.

Planning a decarbonized electricity system involves complex choices due to multiple technological options and sociopolitical constraints. Energy-system design typically relies on cost-optimal models, which may neglect other viable system configurations and overlook social factors essential for political feasibility. The Modelling to Generate Alternatives (MGA) approach, rather than identifying a single cost-optimal solution, explores the space of sub-optimal solutions to generate qualitatively different configurations. This wide range of energy alternatives provides a deliberative space for policymakers and local communities (Lombardi, 2020).

Our aim is to adapt these tools for educational use, allowing students to engage in energy-system design, acquire knowledge repertoires, and support debate among peers, within families, and ideally within their communities.

In the final step, we will test the developed educational tools directly in the schools of the communities involved in the study. Social tensions triggered by the energy transition will be framed as topics for interdisciplinary inquiry, drawing on ethnographic findings and the energy-system model. On this basis, students will be asked to elaborate sustainable and desirable future scenarios and to participate in the public debate within their communities, according to the future-oriented science education approach (Laherto et al., 2023; Levrini, 2019)

Conclusions

Finally, we will evaluate the reception, outcomes, scalability, and potential for further development. We will also assess to what extent these educational experiences contribute to redefining how scientific knowledge becomes embedded in local social life. If these experiences

prove capable of fostering students' engagement in the public debate on the energy transition, they will be consistent with the ideal of communicative rationality.

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Greek Chemistry Teachers' Perspectives On The Integration Of Green And Sustainable Chemistry Practical Activities In Secondary Education

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Green and sustainable chemistry, aimed at minimizing environmental impact and supporting resource efficiency, has gained significant attention in recent decades. This shift has promoted a strong global community of practitioners and advocates, and increased interest in integrating these principles into school and university education. While various strategies have been developed to incorporate green and sustainable chemistry into curricula, there is limited data on the extent of its integration across different countries. This study examines the integration of green and sustainable chemistry into secondary education in Greece, with a focus on practical activities conducted by chemistry teachers. Data were collected from 92 teachers via an online questionnaire, developed for an international survey by the International Union of Pure and Applied Chemistry (IUPAC). Participants reported that averagely 29,9% of their practical activities incorporated green and sustainable chemistry. Moreover, they highlighted the importance of such activities in promoting critical thinking and problem-solving skills, and introducing green chemistry and sustainability through hands-on activities. However, some teachers reported not incorporating such activities, reflecting challenges in integration. Our findings highlight the increasing role of green and sustainable chemistry in education and underline the need for further research concerning its integration into curricula and teaching practices.

Keywords: Secondary education, sustainability, teacher beliefs

Introduction

In an era of growing environmental concern, green and sustainable chemistry has gained substantial interest, leading to the establishment of a robust community of practitioners and advocates within the global chemistry field. Green and sustainable chemistry adopts a holistic perspective through life-cycle analysis and systems thinking, ensuring that sustainability is considered at every stage – from raw material sourcing to product disposal. This comprehensive framework not only advances scientific innovation but also aligns with broader global goals, such as dealing with climate change, conserving resources, and enhancing economic development in harmony with environmental protection (MacKellar et al., 2020).

Green and sustainable chemistry refers to the concept of designing processes and products that improve the way natural resources are used to meet the needs of present and future generations, without causing harmful impacts on humans and ecosystems. It is guided by specific principles that emphasize environmentally friendly methods for conducting chemical reactions and producing chemical products. These principles promote practices such as using environmentally friendly auxiliaries like solvents for reactions and separations and streamlining processes to reduce the number of steps. These ideas form the core of green chemistry, focusing on more sustainable and efficient chemical production (Anastas & Zimmerman, 2019; Clark, 2016).

Over the years, various strategies have been employed to incorporate the principles and practices of green and sustainable chemistry into the chemistry curriculum in secondary education and undergraduate studies. Concerning the latter, some universities have developed independent, stand-alone green chemistry elective courses, others have fully integrated green chemistry

principles throughout their entire chemistry curriculum, and some universities have incorporated green chemistry laboratories as substitutes in laboratory courses (MacKellar et al., 2020). Concerning school education, four basic models of integrating green and sustainable chemistry have been developed: (a) integrating green and sustainable chemistry practices into school chemistry practical activities, (b) integrating green and sustainable chemistry practices as core content within the chemistry curriculum (c) using socio-scientific issues related to sustainability and chemistry as a foundation for learning chemistry and understanding the relevance of green and sustainable chemistry to sustainable development, and (d) using sustainability as a driver for school reform, transforming school life in alignment with sustainability principles, including aspects related to chemistry and its applications (Burmeister et al., 2012).

Focusing on school education, we note that despite the various strategies that have been developed to incorporate the principles of green and sustainable chemistry into the curriculum, it seems that there are not enough data concerning the extent of this integration across different countries. The present study was conducted as part of a global survey coordinated by the International Union of Pure and Applied Chemistry (IUPAC) (Delaney et al., 2024) and aims to investigate the integration of green and sustainable chemistry practices into chemistry practical activities within secondary education in Greece. The research questions addressed are the following:

RQ1: What percentage of the chemistry practical activities that teachers conduct is connected to green and sustainable chemistry approaches?

RQ2: Which factors do teacher consider important when choosing chemistry practical activities to do with their class?

RQ3: Where do teachers normally obtain their chemistry practical activities related to green chemistry and sustainable chemistry?

Methodology

The data of this study were collected through an online questionnaire created within an international IUPAC project (Delaney et al., 2024) and translated into Greek by the authors of this paper. The questionnaire included items concerning the integration of practical activities into teaching of chemistry in general, the integration of green and sustainable chemistry practical activities into teaching of chemistry in particular and demographic questions. The questions included were open and closed ended. Here we are concerned with the part of the questionnaire that deals with the integration of green and sustainable chemistry practical activities into chemistry teachers' practice. More specifically, we report on three closed ended items that concern (a) the percentage of practical activities implemented by teachers that are related to green and sustainable chemistry approaches, (b) the factors that teacher consider important when they choose chemistry practical activities to do with their class, and (c) the sources that the teachers use to obtain green and sustainable chemistry practical activities.

For the first item, participants had to choose the percentage of practical activities they did with their class which was related to green and sustainable chemistry approaches using a slider. For the second item, participants had to answer about the importance of four factors when choosing chemistry practical activities to implement into their teaching using a 5-point Likert scale. More specifically, they had to answer whether the following factors were "not at all important" (1), "slightly important" (2), "moderately important" (3), "very important" (4) or "extremely important" (5) when choosing practical activities to use in class: (i) the practical activity is clearly linked to local environmental issues, (ii) students find green chemistry and sustainability issues and topics engaging, (iii) practical activities are a way to introduce green chemistry and

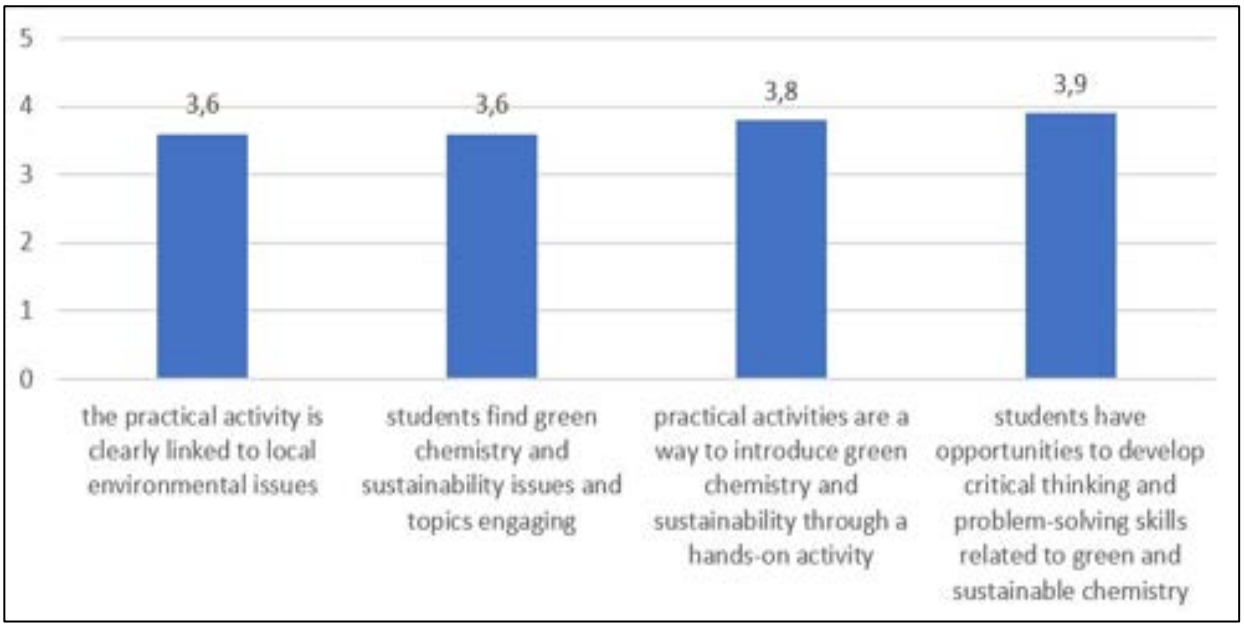
sustainability through a hands-on activity, and (iv) students have opportunities to develop critical thinking and problem-solving skills related to green and sustainable chemistry. Finally, for the third item participants had to answer how they obtain green and sustainable chemistry practical activities among the following choices: (a) learned from other teachers, (b) learned during university studies/teacher training (pre-service), (c) learned during professional development after starting teaching career (in-service), (d) read about in a magazine or online, (e) heard about at a conference, (f) designed myself, (g) other, (h) I do not consider green or sustainable chemistry activities in my teaching.

The part of the questionnaire that concern us in this paper was filled in by 92 teachers teaching chemistry in secondary education in Greece. They were selected by convenience sampling (Bryman, 2012) and they agreed to participate in the study after receiving (i) detailed information about the study's objectives, and (ii) confirmation that their participation would remain anonymous. Concerning their experience in teaching chemistry, 7 teachers answered that it was their first year, 13 teachers had 2-5 years of experience, 25 teachers had 6-15 years of experience, 38 teachers had 16- 30 years of experience, and 9 teachers had more than 30 years of experience. Finally, 12 teachers stated that they were currently teaching in Grade 7, 33 teachers were currently teaching in Grade 8, 35 teachers were currently teaching in Grade 9, 56 teachers were currently teaching in Grade 10, 52 teachers were currently teaching in Grade 11, and 59 teachers were currently teaching in Grade 12. It should be noted that in most cases the participating teachers were teaching in more than one Grade in order to complete the required schedule.

Results

The mean percentage mentioned by participants concerning the implementation of green and sustainable chemistry practical activities was 29,9. It should be noted that the standard deviation was quite large (26,9) indicating that there was a high level of variability within their answers.

Figure 1. Average importance of factors concerning selecting practical activities for classroom use.

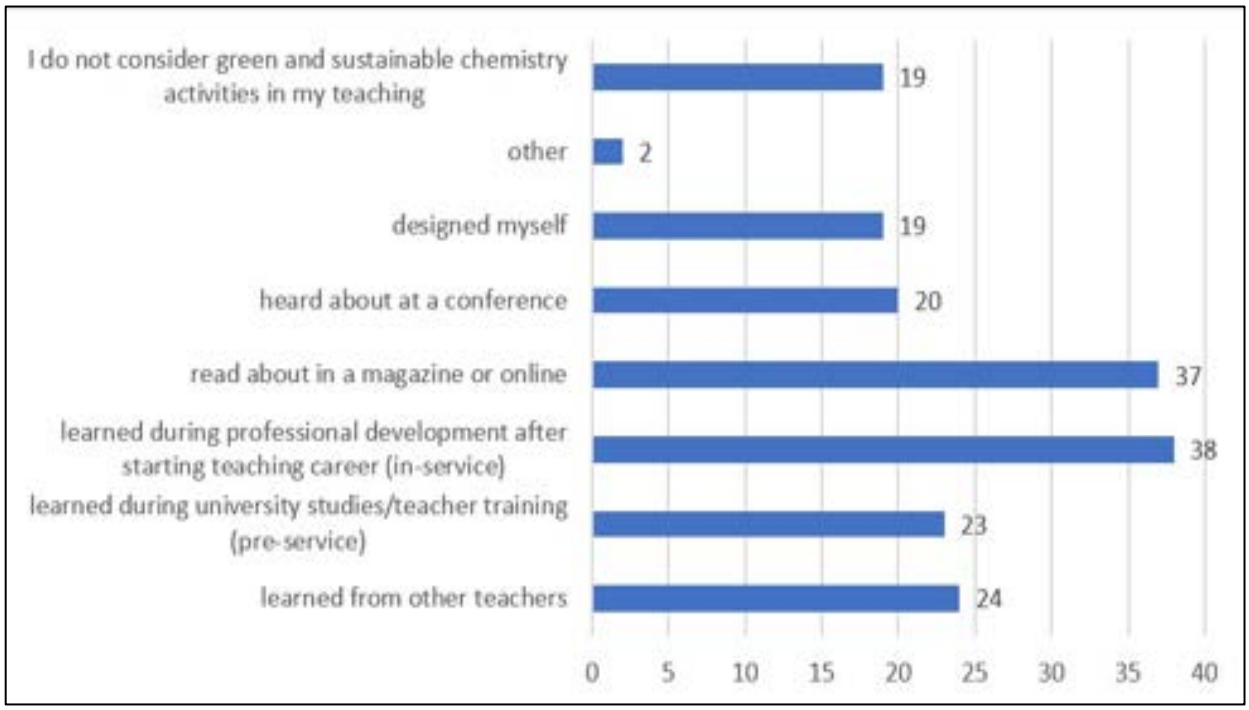


Regarding the factors that the participants considered important when choosing practical activities, it seems that the most important factor was that through them students have opportunities to develop critical thinking and problem-solving skills related to green and sustainable chemistry. We noticed that averagely all factors that had to do with green and sustainable chemistry were considered rather important by the participating students concerning

selecting practical activities for their teaching (Figure 1).

Finally, concerning the sources that teachers use in order to obtain green and sustainable chemistry practical activities, it seems that the most popular ones are continuing professional development programs (38) and magazines/online sources (37). It is worth noticing that several teachers answered that they do not consider green or sustainable chemistry activities in their teaching (19) (Figure 2).

Figure 2. Frequencies of sources that teachers use in order to obtain green and sustainable chemistry practical activities.



Discussion

Green and sustainable chemistry has gained significant attention in the last decades, enhancing the development of a strong community of practitioners and advocates in the global chemistry landscape. Moreover, it seems that a strong interest in ways to integrate the approaches of green and sustainable chemistry into education has also been developed (Dicks & Bastin, 2019). Green and sustainable chemistry education has been present in educational research and practice already from 1990s. Zuin et al. (2021) researched the number of papers that concerned green and sustainable chemistry education and reported that more than 500 papers were available in the literature spanning a period from 1998 to 2021. Most of them focused on developing curricular materials and evaluating student learning outcomes and attitudes. Discussing their results, the authors concluded that various institutions have created tools and resources to facilitate the integration of green and sustainable chemistry into high school and even elementary education.

While several strategies have been developed to embed the principles of green and sustainable chemistry into curricula, there appears to be a lack of sufficient data on the extent of this integration across various countries. In this study we investigated Greek chemistry teachers' practice and ideas concerning green and chemistry practical activities and some interesting results arose. For example, it seems that a considerable percentage of the practical activities conducted in their class concerns green and sustainable chemistry approaches. Moreover, participants seem to find the dimension of green and sustainable chemistry rather important when they choose practical activities to implement into their teaching. For instance, they averagely assigned a 3,9 score (ranging from 1 "not at all important" to 5 "extremely important") to the importance of

practical activities offering students the opportunity to develop critical thinking and problem-solving skills related to green and sustainable chemistry.

Finally, regarding the sources that participants use in order to obtain green and sustainable chemistry practical activities, it seems that the most popular one was continuing professional development programs. This may not agree with relevant literature at certain level, since chemistry teachers around the world seem to mention the lack of in-service training as a main barrier to integrating green and sustainable chemistry content into their teaching (MacKellar et al., 2020). Other popular source of green and sustainable chemistry practical activities were magazines and online sources, while fewer participants stated that they obtained a practical activity by attending a conference or they designed it themselves. We should note that some teachers reported not incorporating green and sustainable chemistry practical activities in their teaching, reflecting challenges in integration.

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Science Teachers' Democratic Assignment: A New Vision Of Scientific Literacy And Civic Engagement For A Futuristic, Fair And Sustainable Europe

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There are calls today from several directions, including from UNESCO 2021 for a new social contract for education, and by implication science education. This begs the question what this might mean for the framing of scientific literacy and civic engagement in a futures-oriented Europe, aspiring for fair and sustainable green and digital transitions. This newly desired subjectivity, centred on repairing former colonial injustices, requires reimagining a new vision of scientific literacy and civic engagement, one that is attentive to human emancipation, and to the knowledge(s), cultures, ethical values, care and justice needs of a fair and sustainable economy, society and environment. Here I draw from Mooney Simmie and Edling's (2019) theorisation of Teachers' Democratic Assignment (TDA), Giroux (1988/2024) and Hordern's (2024, 2022) theorisations of teachers' identities and knowledge base, and Bang's (2017) assertion of the ontological indeterminacy embedded in science education. I use these theoretical perspectives to critically scrutinise the mainstream framing of scientific literacy and civic engagement, and to consider the exponential growth in the literature of an alternative emancipatory framing of science TDA for learning to live well with others in pluralistic democracies. The study reveals a reframing of science TDA in the direction of a knowledgeable, care-based, critically reflexive and activist citizenry in a highly complex, scientific and technological world. The emerging critical insights reveals that reframing science TDA needs to move beyond evidence and externally provided norms and to include the interruptive power of the arts, humanities and the deliberative traditions.

Keywords: *scientific literacy, civic engagement, science teachers' democratic assignment*

Introduction

Since the start of this century, and the policy imperatives embedded in a fast-globalising education reform movement, the education and training of science teachers, their identities and knowledge base, are often defined within reductionist views of science teacher's responsibilities in relation to the preparation of young people for a life of active engaged citizenship. While citizenship, and becoming a citizen, rests on a political concept of membership of a nation state, the concept in general education today, and in science education is more often framed as a neutral and apolitical concept unrelated to power and privilege and whose interests are being served. It may well be that, working within the boundaries of the nature of science, and scientific pedagogies, science teachers' task is confined to primarily providing a scientifically literate population, for the ever-changing qualification and socialisation needs of the economy and society (e.g. the pipeline of talent) and within an appreciation of science-in-society and real-world applications.

Levrini et al. (2025) argue the this mainstream framing of science education is underpinned by a rather naïve positivistic framework, where there appears to be little or no requirement for science teachers to engage young people with the messiness of real world ethical, scientific and political dilemmas and/or to build capacities to interplay with other knowledge(s) and ways of knowing (e.g. cultural and historical memory) in order to critically question, debate and debunk issues of public interest values (e.g. climate change) so pertinent today for the successful future of democratic societies and the planet.

There is already a pressing need recognised by the European Commission in Europe to reframe education and skills, and by implication the relations between scientific literacy and civic engagement for a futures-oriented fair and sustainable green and digital transition (Mooney Simmie, 2025b). How this is to be done in theory, policy and practice remains an open question and one this is increasingly complicated by the neoliberal imaginary underpinning science education, including scientific literacy and science teachers' work practices (Mooney Simmie, 2025a, 2023). Neoliberalism continues to act as a highly successful and hybridised project of governance in science education today. Sant (2019) reveals that this political project of governance relies on an ideological governing form that is anti-democratic at heart and based on the normalisation of elite ruling by (scientific) experts and market leaders. Neoliberalism therefore frames science teachers' knowledge base and practices in the direction of evidence-based and standardised practices, all known in advance, manageable and measurable (Mooney Simmie & Tolbert, 2025).

This neoliberal framing of science education is taking place at a time of unprecedented change in Europe, a time of marked increase in the rise of injustices and fascist ideologies. The historian, Gerstle (2024) argues that the neoliberal social order, rising to prominence in the 1980s nowadays reveals serious fault lines, especially since, the global recession in 2008-2009, the rise of technoscience and the unprecedented threats to the western economy and democratic politics by the Trump administration in the US (Tolbert, 2025).

UNESCO's *Reimagining Education Report* (2021) asserts a new urgency for general education, and science education, to arrive at a new social contract and to build capacities to repair past injustices of colonisation. The UN Sustainable Development Goals act as a blue print for this social contract that aspires, amongst others, to end poverty, secure climate justice and digitisation through empowering new transformative social partnerships. The American philosopher of education, John Dewey, asserted that democracy is remade with each new generation and that education, and science education, always acts as the mid-wife of democracy (Dewey, 1916/2024). This begs the question how democracy is discerned in science education, and in science teachers' felt sense of obligation to democracy, in a future-oriented science education and its relation to scientifically literate and activist citizens.

Theoretical Perspectives

Here I draw from critical and feminist perspectives to frame the problem of *Science Teachers' Democratic Assignment* (STDA) as a sociological problem connected to the teachers' obligation for a humanising and (re)constructivist discourse of science education embedded in a relational ethic of care and justice, in theory and in practice (Mooney Simmie & Edling, 2019). From this way of reasoning democracy is positioned as an ever-changing politics in the wider society whose purposes, principles and practices change as change is needed in the economy, society and the environment. Unlike systems of majority rule, democracies by design are always in the political direction of equality, diversity and justice, with stated protections for the rights of minorities.

A feminist perspective places the human subject (subjectivity) at the heart of science education as a relational and dialogical practice that pays attention to the situational and the interplays between knowledge(s) and different ways of knowing, In this way, a critical and feminist framework for science education positions science teachers' identities, knowledge base, and work practices more as a cultural problem – with science teachers as public intellectuals with cultural responsibilities and obligations rather than as clinicians, technicians and/or as mere delivers of instruction for a system of compliance (Giroux, 1988/2024; Howie, 2020).

While Levrini et al. (2025) reveal the naïve positivism underpinning the mainstream framing of

science education and scientific literacy today, the science educator Lars Bang draws on the postmodern work of Deleuze to reveal the necessary ontological indeterminacy and crack at the heart of science education (Bang, 2017). This way of reasoning is further supported by the theorisation of the science educator, Jesse Bazzul, who starts from the paradoxical premise that the purposes of science education are multiple and contradictory, that can be grasped as a perpetually open ethical question that seeks to, on one hand conserves culture and heritage, and on the other, leaves the way open for the new to emerge.

What might this mean for science teachers' knowledge base today and for a future of uncertainty? Will it be sufficient for science teachers to have access to constant upskilling and reskilling in content knowledge (e.g. knowledge of science and science pedagogies), and externally provided norms and values, or will something else be needed? Given that feminist perspectives foreground intersectionality, the human at the centre and the relational capacity for teacher-student dialogue, and critical theories highlight the need to develop critical consciousness, for the affective equality needed for the greater good of society and public interest values (Lynch & Crean, 2019), then policies of content knowledge and externally provided norms, while necessary will be far from sufficient to assure scientific literacy works for a futures-oriented citizenship tasked with human emancipation, and the greater good of fair, sustainable and care-based pluralist democracies and eco-friendly environments.

In teasing out teachers' knowledge base today, drawing for the concept of teaching as an advanced professional practice, Hordern (2022, 2024) presents a three-dimensional concept that aligns well with the argument above. Hordern theorised that (science) teacher's knowledge base is nuanced and sophisticated and calls on knowledge(s) and different ways of knowing that needs access to three distinctive sources: (1) the sciences (2) the arts and humanities and (3) the deliberative traditions.

This three-dimensional concept of science teachers' knowledge base accepts the premise that science teaching needs access to the sciences for sense making practices, to the foundational disciplines in the arts and humanities - such as, philosophy, history and sociology – for strange making practices, such as, interruption of the discourse to leave spaces open enough to think otherwise, for the not-yet-thought, to sap power, and finally, access to the deliberative traditions, so that science education is understood as a holistic and dynamic practice for a desired subjectivity that is considered to be more than the sum of the parts.

Aims And Research Questions

This contested literature opens new spaces for reclaiming and reframing scientific literacy and civic engagement, and especially for consideration of what it means to be a desired human subject today (subjectivity) in a complex and highly scientific and technological society. The study therefore aimed to conduct a critical scrutiny of a select literate, albeit a limited and small scale study of the contemporary literature to better understand how fresh calls for a new social contract today in science education for a fair and sustainable Europe need to play out differently from a neoliberal imaginary and what this might mean for science teachers' knowledge base and for a new and different vison of science teachers' democratic assignment (STDA).

Findings

The framing of the purposes of science education in the life of the young person in schools today, and its relation to the journey of human becoming (subjectivity) as a scientifically literate, engaged and active, if not fully an activist, citizen is deeply contested in the literature of science education. What started off in the 1950s, as a desire for a scientifically literate general population, with a positive disposition toward science, and to support publicly funded scientific research has

changed, even if not dramatically, to different visions of 'scientific literacy', and also found in such concepts as contextualised images of Science-in-Context, and Science-in-Society and more recent notions of 'citizen science', 'transformative science' and 'argumentation'.

The concept of scientific literacy itself has gone through multiple iterations since the 1950s (Bybee & Mc Crea, 2011, Roberts, 2007). The rationale behind the concept was to develop an uncritical appreciation of science and science research and to identify a pipeline of elite talent (abstract thinkers) to enter career pathways in the sciences, and as researchers connected to economic competitiveness and national security. The first vision, Vision I centred on propositional knowledge, while the more recent vision, Vision II while connected to contexts and to real world applications was largely confined to a notion of human becoming that Bang (2017) identified as a 'Cartesian understanding of knowledge and Cogito, the Dogmatic Image of Thought' (p.810). More recently, a third vision, Vision III seeks to reclaim science education as a human centred and socio-cultural endeavour, a sociological project whose rationale in concerned with supporting a transformative view of science education. Sjostrom & Eilks (2021) present Vision III as a *Critical Reflexive Scientific Literacy,* drawing from the Northern European concept of *Bildung* and its connection to holistic traditions for an expansive notion of education for human development in the wider world rather than confined to curriculum studies.

Ast the same time as the ongoing development of scientific literacy for a new vision of a scientifically literate citizenry, Bencze et al. (2020) reveal the forty year history of struggle in the science education literature and in globalising reforms, reframing a rich variety of constructs seeking to connect school science to society and the wider world, such as *Science-in-Context*, *Socio-Scientific Issues* (SSI) and *Critical Science Questioning*.

More recently, the science education literature and policy reforms are framing new notions of 'citizen science' and 'argumentation' as novel ways of reconnecting science and scientific literacy to new notions of engaged citizens, often apolitical notions of what it means to be a citizen in a nation state and/or in the wider global world today. For example, a study by McNew-Birren & Gaul-Stout, 2022) taking pace in an urban research centre in Milwaukee, Wisconsin in the US constructed 'citizen science' and positioned citizen volunteers as additional place-based 'data gatherers' for the research centre, provided with the necessary resources of equipment and technical training, rather than any collectivist (political) notion of citizenship in relation to how ethics, science, and politics plays out for the greater good of society, economy and the environment. In a similar, and related construct, a notion of 'argumentation' in science education is currently employed for debating socio-scientific issues while drawing only from science, analytical thinking, data and empirical evidence. Kim & Roth (2018) reveal the process involved when children and young people are coached in higher order thinking to support these domain specific skills of argumentation. In this way, the concept of 'argumentation' appears tightly confined to Bang's (2017) 'dogmatic image of thought' where right answers are valued, dialogue with other ways of knowing are closed down, and there is no recognition of the necessary ethical and political dilemmas and/or struggles with multiple knowledge(s) and different ways of knowing. In this regard, the diversity of new constructs seeking to connect scientific literacy to the development of engaged citizens today, largely disappoints given that they are often under-theorised and assume a normative consensus (Mooney Simmie & Tolbert, 2025).

A New Social Movement Reimagining Science Education

At the same time, there is also a deeply contested science education literature, and a growing global social movement, involving science education researchers in the US, New Zealand, Australia, UK and Canada with advocacy for Reimagining Science Education in the Anthropocene – the term given to the geological footprint in the planet largely coming from man-

made exploitation of the Earth's natural resources (Tolbert et al., 2024; Wallace et al., 2022). This fast-globalising social movement reveals inherent dangers in viewing science education and its relation to society and the planet in reductionist ways. Instead, they advocate for a philosophically grounded and problem-posing approach to science education which can humanise the discipline and leave sufficient open spaces for scientific, critical and reflexive literacies and futures thinking about the importance of scepticism in science education and its ethical and political relation to personal, social and planetary justice.

Critical pedagogy researchers in science education, such as Hodson (2003), and feminist thinkers in science education, such as Colucci-Gray (2014) reveal how novel concepts in science education, scientific literacy and civic engagement are all hampered in different ways by the rather naïve positivistic framing of science education that continues to persist in mainstream policy and research in neoliberal times (Bang, 2017; Bazzul, 2023; Levrini et al., 2024). Howie (2020) a school principal in Australia shows how this political project frames education and teaching for compliance and self-imposed responsibility rather than agency:

In closing down dialogue and setting normative standards, an evidence hierarchy is inherently anti-democratic, as it closes the public space, so to speak, reducing social relations to obligation. The barriers of the political-administrative establishment go up around the public educational research space. What should be open to question and not reductively represented as self-evident, including research methodologies and outcomes, are standardised and ranked (p.683).

Discussion And Conclusions

The selected theoretical lens used here became a powerful explanatory framework for interrogating the contemporary problem of how to reframe scientific literacy and civic engagement in ways that are actively connected to the socio-scientific, ethical and socio-political issues of the moment, and for a futures-oriented, fair and sustainable Europe. Based on the critical insights emerging, albeit from what was a small scale study of a select literature, a number of key research questions emerged that can guide this new framing of STDA in a future of uncertainty, where science will need to play out in a futures-oriented science classroom in ways that are problem-posing, philosophically grounded, and connected to the critical consciousness needed for the greater good of a desired subjectivity, society and planet (Mooney Simmie & Moles, 2025)

Starting with Hordern's (2022, 2024) rubric, any reframing of STDA will clearly need to draw from the three-domains of science teachers' knowledge base in ways that are inclusive of the meaning-making and interruptive power of the sciences, arts and humanities respectively, as well as the deliberative tradition that secure the holistic and dynamic nature of science education. Besides, any new framing of scientific literacy and its connectivity to civic engagement will need to offer affordances for critical appraisal of the power and limits of evidence and rely on an interplay with a rich variety of literacies found, for example, in the sciences, ethics, politics and in ways that can release the transformative potential of the learner for care based, fair and just sustainability (Colucci Gray 2014).

In conclusion, the following key questions emerged from the study as a preliminary way of distinguishing between a neoliberal framing of STDA for compliance with the contemporary social order (status quo), or for affordances for human emancipation and a futures-oriented fair, just and sustainable economy, society and planet:

How are science teachers' democratic assignments (STDA) framed - as a problem-solving exercise or as a philosophically grounded problem-posing exercise?

Are science teachers expected to interplay with other literacies, values, cultures, knowledges and

different ways of knowing in relation to the necessary (scientific, ethical and political) struggles with contemporary issues in the wider world?

Are science teachers expected to engage in the deeply personal work of critical reflexivity to improve their self-awareness and justification of selections?

Are science teachers required to challenge and to move ('affect') their students to action (affectivity) in relation to socio-scientific issues of injustice in the wider world?

Are science teachers expected to develop students' capacities for an appreciation of science-in-society and/or for a critical appraisal of the power and limits of science?

The critical insights emerging suggest that a problem-posing and transdisciplinary approach is needed in any new reframing of science teachers' democratic assignment (STDA), a framing that will need to be inclusive of the sciences, the arts and humanities for the necessary productive clashes between their sense-making and interruptive powers, and the deliberative traditions. This supports Bang's (2017) assertion of ontological indeterminacy and the need to hold any new framing of scientific literacy and civic engagement open to scrutiny and problem posing while providing productive pedagogical spaces in the science classroom and school for dialogue, critical debate, and provocation for eliciting self-awareness, agency and action to occur.

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Empowering Children As Agents Of Climate Action: A Case Study Of A Teacher's Enactment Of Socio-Scientific Inquiry-Based Learning In A Kindergarten

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Kindergarten-aged children, although often considered to be too young, have the right to know about the uncertain world they are living in and to have their voices heard in climate action. Climate change education equips students with the knowledge, skills and values of climate change, and empowers students for climate change mitigation and adaptation. However, children in kindergartens tend to receive less education in climate change compared to other school periods, and teachers often lack the subject knowledge and teaching skills needed to address climate change with kindergarteners. To explore how early childhood teachers can enact climate change lessons in age-appropriate ways, we implemented a teacher professional development programme, which supported teachers to enact four climate change lessons based on the socio-scientific inquiry-based learning (SSIBL) approach consisting of three stages (Ask, Find out, and Act). In this proposal, we present a qualitative case study focusing on how one teacher enacted her lessons in a kindergarten in Shanghai, China. Semi-structured interviews, lesson video recordings and teacher's reflection journals were collected and analysed qualitatively. The findings of instructional strategies the teacher used in each SSIBL stage are: (1) Ask - the teacher created a need to know with personally and locally relevant topics about climate change; (2) Find out - the teacher used iconic representation to help children concretise their reasoning process in personal inquiry, and used a sensory approach in scientific inquiry to teach abstract scientific knowledge; (4) Act - the teacher encouraged children to take indirect climate action through family or community stakeholders.

Keywords: climate change education; early childhood science education; socio-scientific inquiry-based learning

Introduction

For the sake of addressing climate change urgently and promoting sustainable development, the United Nations (2017) proposes to empower climate action through education such as curriculum inclusion and teacher education. Climate change education (CCE) entails equipping students with knowledge of the concepts, causes, impacts and solutions related to climate change, as well as the skills, values and attitudes needed to empower them for climate change mitigation and adaptation at local and global scales (Hung, 2014; Kavanagh, Waldron and Mallon, 2021). Young children are more likely to act in a pro-environmental way than they are in later life (Collado et al., 2015), making this period critical for CCE by developing their knowledge and attitudes and building the foundation for future learning. However, the challenges posed to young children by complex and abstract knowledge (Copple and Bredekamp, 2009) and the lack of teachers' relevant background knowledge (Kavanagh et al., 2021) might be reasons that inhibit CCE in early childhood education.

Climate change as a socio-scientific issue (SSI), involves controversial opinions on how it impacts society with a connection to scientific concepts and applications (Zeidler, 2014). In this research, the pedagogical framework of socio-scientific inquiry-based learning (SSIBL) (Levinson, 2018) is adapted by teachers to enact climate change lessons. SSIBL has three practical stages: (1) Ask - asking authentic questions and creating a need to know related to SSI; (2) Find out – finding the evidence for answering the questions through inquiry-based learning, which includes scientific, social and personal inquiry; (3) Act – taking action to address SSI.

SSIBL involves integrating SSI into classroom teaching that leads to action-oriented CCE where children are empowered to make informed decisions and take action.

To address the scarcity of CCE studies in early childhood, this research explores the strategies of teaching about climate change used by a kindergarten teacher, with support from a teacher professional development (TPD) programme that included the subject knowledge of climate change and the teaching skills aligned with SSIBL. The overall research question was: What strategies do an early childhood teacher use to enact climate change lessons based on the SSIBL approach?

Methods

Teacher Professional Development Programme

In accordance with Desimone's (2009) five core features of the effective TPD programme - content focus, active learning, collective participation, coherence and duration - we developed a TPD programme that consists of four workshops, to prepare teachers with the subject knowledge of climate change (Workshop 1) and the SSIBL pedagogy (Workshop 2) for enacting the climate change lessons. Workshops 3 and 4 facilitated teacher's reflection on what they had done and for improving lessons. Teachers attended Workshops 1 and 2 before they selected teaching topics related to climate change and then co-designed the four lesson units. Following that, teachers enacted Lessons 1 and 2 before they attended Workshop 3 and enacted Lessons 3 and 4 before Workshop 4. The programme spanned four months, from March to June 2024.

Participants And Data Collection

This study is a qualitative case study. Four teachers participated in the TPD programme, but in this proposal, we focus on one teacher's experience for an in-depth analysis. The teacher had been teaching in kindergarten for 11 years and was working with children aged 5-6. This teacher had been living in Shanghai for 39 years and had some familiarity with the impacts of climate change that Shanghai experiences. The research context was a public kindergarten in Shanghai, China, that follows the governmental kindergarten educational policy of enacting inquiry-based science learning.

Data were collected through semi-structured interviews, lesson video recordings, and the teacher's reflection journals to explore how the teacher enacted the action-oriented climate change lesson with the SSIBL approach in kindergarten. Three semi-structured interviews were conducted. The initial interview was conducted before the TPD programme, to find out about the teacher's background and her understanding of climate change and inquiry-based learning, so that the workshops can be designed to better support their subsequent lesson enactments. The mid-interview was conducted after Lesson 2, focusing on the teacher's rationale for choosing teaching topics and enacting certain instructional strategies of Lessons 1 and 2. At the end of the programme, the teacher's rationale for certain instructions of Lessons 3 and 4 was explored in the final interview. Four lessons were video-recorded to observe what and how the teacher enacted in the classroom. The interviews conducted after observing the teacher's lesson enactment can improve the reliability of interpretation (Desimone, 2009). Teacher reflection journals were recorded throughout the TPD programme and focused on her experience and feelings about lesson enactments and participation in workshops.

Data Analysis

The interviews and teachers' reflection journals were analysed by thematic analysis (Terry et al., 2017). The lesson video recordings were first segmented into episodes based on activity, and then the activity contents were summarised. Secondly, the lesson recordings were transcribed into

written documents, and the classroom discourse was coded based on two frameworks. One framework focuses on the dimensions of SSIBL, such as the codes 'Contextualise the controversy to a locally/personally relevant experience' 'Encourage action taking through indirect action' etc. The other framework is about accountable talk (Michaels et al., 2008). The teachers' talk moves were coded deductively from this framework to represent the functions of the discourse and how it interacts with SSIBL. Sequentially, the codes were categorised by the three stages of SSIBL (Ask, Find out and Act), to explore what strategies the teacher used for each SSIBL stage in CCE within a case. The rationales for the teacher's use of the strategies were compared with the data from interviews and reflection journals.

Findings

The analysis revealed the teacher's strategies for CCE in early childhood based on the SSIBL approach. We present the strategies of how the teacher enacted each SSIBL stage (Ask, Find out and Act) for teaching climate change to her 5-6-year-old class of 15 children.

(1) Ask stage: Creating the need to know by contextualising locally and personally relevant controversy related to climate change

The teacher asked the children to survey the local neighbourhood regarding the changes of green spaces being replaced by car parks before the lessons. As shown in Table 6.1, the teacher illustrated the dilemma that existed in the neighbourhood with pictures (turn 5), and raised an open question 'Should we build car parks or green spaces in the community?' (turn 7) to invite children's ideas for further inquiry activities. She introduced the issue from real life that is personally and locally relevant to young children, to create a need to know related to climate change.

Table 1. The Ask stage in Lesson 1 was implemented by the teacher.

Turns	Speaker	Lesson discourse	Codes
5	T	Oh, this is the community being renovated, right? The neighbourhood committee issued a notice. This notice, said that the neighbourhood was going to be renovated. What was being renovated? Some parents of children said that there are not enough parking spaces in the neighbourhood, and they want to add more parking spaces. Some people said that they like greening, right?	Contextualise the controversy to a locally/personally relevant experience; Raise authentic/open questions; Invite students to express personal opinions;
6	T	So let's have such a voting [activity].	
7	T	Hey, do you think we should add more parking spaces or increase green spaces?	

The teacher elaborated on the importance of personal experiences when discussing her rationale for choosing this topic and designing such an activity in her mid-interview:

> 'Neighbourhood conversion is something this area has been going through recently, so I think that personal experience is more useful to inspire children to learn more about this [climate change] topic.'

(2) Find out stage: Iconic representation (e.g. drawings) serves as a communication tool, helping young children concretise their reasoning process in personal inquiry

The teacher gained additional information about children's opinions through their drawing, in terms of their choice of keeping car parks or green spaces, to press for further reasoning, as shown in the example in Table 2.

Table 2. Analysis of the teacher's lesson discourse in personal inquiry in Lesson 1.

Turns	Speaker	Lesson discourse	Codes
38	T	Which child drew this point of view [in the picture]? I will invite him to talk about it.	Iconic representation Encourage reasoning
39	S7	My family has a car, so I want to draw a parking garage. There are always many parking spaces in my community, but they are all taken by other people, so I want to build a parking garage.	Invite students to express personal opinions (say more)
40	T	Well, she built a parking garage here, so why is there green on it [car park -the bottom right part of Figure 6.2.2]?	Support students in deepening their reasoning drawing on everyday life
41	S7	I think the parking garage is pretty hot. I'm going to make some vines to cover it so it won't be that hot.	

The teacher encouraged Student 7 to share her reasons for supporting increasing the car parks with the picture (turn 38). From the student's response, the teacher realised that the viewpoint expressed in Student 7's spoken language did not entirely correspond to the one she sought to represent in her drawing (turn 39, Figure 1), so she pressed further reasoning by asking what the green stuff above the car park in her drawing (turn 40). From Student 7's response in turn 41 about how to keep the car park while keeping green spaces, the teacher then better understood that Student 7's choice was not only in support of the car park drawing on her family experience in turn 39, but also seeking a balanced solution to the issue. In the teacher's lesson, the drawing represents the child's complete ideas that helped the teacher identify the child's additional unarticulated personal thoughts and made the child's reasoning process visible.

Figure 1. Student 7's picture visually represents her personal opinions on whether to keep green spaces or build car parks.



(3) Find out stage: Using a sensory approach in scientific inquiry to teach abstract scientific knowledge as evidence for climate action

In Lesson 2, the teacher taught children to learn about the cooling effect of the trees. The children felt different temperatures under the trees and in the places without the trees, by touching different materials (i.e. floor, tile, soil), as shown in Figures 2 & 3, during the extreme hot weather in Shanghai at the end of May. The teacher simplified the complex principles behind the cooling effect produced by trees through transpiration and shading into a scientific phenomenon that could be used as evidence for making informed decisions by using a sensory approach.

Figure 2. Children were feeling the temperature under the trees..



Figure 3. Children were feeling the temperature in places without trees



The teacher used the senses to make the scientific knowledge accessible to young children, such as why planting trees contributes to reducing the temperature, and adapted to the hot weather caused by climate change in Shanghai. The teacher discussed that the young children can learn about science by using a sensory approach in her reflection journals:

> 'It is easy for students to learn through feeling and touching, but when knowledge is taught in the form of abstract theory, it is difficult for children to understand.'

(4) Act stage: Encouraging young children to take indirect climate action through family or community stakeholders

In Lesson 4, the teacher led children to draw posters in relation to protecting the trees, put up their posters at the school gate, and encouraged children to introduce their solutions to their families when they go back home (Figure 4).

Figure 4. Posters drawn by children advocating for tree protection as a climate action.



The teacher believed that because children's ability is limited, what they can do is to take indirect climate action by encouraging their family and others to take direct action. She said in her final interview:

> 'The ability of children is to encourage the adults, that is, the adults in their family, and then go on to contribute more to society. Their ability is only to change a small part of the people around them and to change their own mind first before they can help more people.'

Discussion And Conclusions

The teacher's instructional strategies in this case study indicate more possibilities of having CCE in early childhood with the SSIBL approach. Although the knowledge of climate change is often claimed to be too complex and abstract for kindergarten children, this study suggests that the teacher is capable of teaching climate change to children through everyday experiences (Ginsburg & Audley, 2020) that are personal and locally relevant to them, by being immersed in a contextualised learning scenario related to climate change, and inquiring through iconic representation and sensory appraoch. These strategies can help young children develop their conceptual understanding and empower them as agents of action.

This research contributes to the theoretical knowledge on how SSIBL can be enacted as an action-oriented approach for CCE. The implications for teachers and teacher educators will involve guiding them in adopting age-appropriate approaches to teaching climate change and enacting SSIBL.

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Facing Scenarios Of Ontological And Epistemic Uncertainty In Science Teaching: Perspectives On Agency In The Literature In The Field

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Advances in science and technology have intensified social and educational challenges in which uncertainty shapes how individuals and collectives are able to act. In science education, this calls for approaches that promote students' agency, understood as the capacity to participate meaningfully in knowledge construction and to act in uncertain contexts, rather than merely acquiring established knowledge. This study examines how the literature has conceptualised and promoted agency in situations and scenarios of uncertainty within science education. A systematic literature review was conducted using the ERIC and Web of Science databases, resulting in the selection of 15 relevant articles. The analysis identifies two main macro-trends. One, predominantly associated with European research, conceptualises agency in future-oriented educational approaches that emphasise collective and projective forms of action, using narratives, simulations and interdisciplinary practices to engage with ontological and epistemic/epistemological uncertainty. The other, largely linked to studies from the United States, focuses on agency as students' participation in scientific practices, highlighting epistemic and consequential agency in contexts of epistemic and conceptual uncertainty. Although distinct, these approaches are complementary in showing how different forms of agency emerge in response to different types of uncertainty. The findings suggest that science education should integrate these perspectives to support students in developing agency to act, decide and take responsibility in complex and uncertain worlds.

Keywords: agency / uncertainty / literature review

Introduction

The world we live in has become increasingly complex as advances in science and technology have confronted us with challenges whose outcomes are ever more uncertain. New challenges such as climate change, artificial intelligence, food security, genetic engineering, and energy transition, among others, have required action under conditions of risk and uncertainty that do not lend themselves to simple solutions, since neither accumulated knowledge nor our projections are capable of providing the certainties, we seek (Giddens, 1990; Beck, 1992, 2009; Rosa, 2020). Schools face the challenge of preparing students to deal with problems of this kind, while simultaneously attempting to reinvent themselves in order to position their practices within this changing world.

Historically, determinism has constituted the foundation of science and, consequently, of science education (Levrini et al., 2024), sustaining the idea that, once the initial conditions and governing laws of a system are known, its future behaviour can be predicted with precision. This epistemological environment contributed to the construction of an image of science as a producer of certainty, control, and predictability. However, social and scientific developments have shown this view to be limited and insufficient. Contemporary understandings of complex systems reveal that natural and social phenomena are frequently non-linear and composed of multiple interacting variables (Prigogine & Stengers, 1984; Funtowicz & Ravetz, 1994). Moreover, uncertainty has become an inseparable element of the scientific process of knowing and acting in the world,

including in its various forms of appearance, such as epistemic, ontological, scientific uncertainty, *etc.* (Kirch, 2012; Njå et al., 2017). Recognising complexity and uncertainty in natural and social processes is therefore fundamental to a more comprehensive understanding of the world we inhabit and of the role attributed to scientific knowledge in the education of citizens (Pietrocola & Souza, 2019).

The OECD (2019), in the report *The Future of Education and Skills 2030*, states that students must be prepared for "the mobilisation of knowledge, skills, attitudes and values to meet complex demands in situations of uncertainty" (p. 25). Accordingly, science education must move beyond the transmission of deterministic knowledge and incorporate explicit engagement with uncertainty and with ways of acting in contexts marked by its presence. Scientific education must acknowledge that we live in an increasingly volatile, uncertain, complex, and ambiguous world, requiring the construction of an ethical stance towards scientific knowledge that assigns responsibility to students as agents in the construction of desirable futures (Bell, 1998). This calls for progress towards a more transformative conception of scientific literacy, one capable of fostering participation, social activism, and agency in response to contemporary challenges (Valladares, 2021).

Within the literature, particularly in approaches that mobilise socioscientific issues, decision-making occupies a central place in the analysis of students' actions. While this emphasis has contributed to shifting science education beyond the mere transmission of content, understanding formative processes exclusively through the lens of decision-making proves conceptually limited, especially in complex situations. Such an approach tends to capture only isolated moments of action, often conceived as discrete rational choices, while overlooking the temporal and social conditions that structure the very possibility of deciding (Emirbayer & Mische, 1998).

It is within this context that the notion of agency offers a more robust analytical framework for thinking about action in socioscientific situations. Some studies have addressed how agency can be promoted in educational contexts where students encounter complex and uncertain problems. However, to date, there has been no work synthesising these contributions in a way that supports reflection on science education in a world marked by uncertainty, where traditional school knowledge was not designed to prepare citizens capable of acting and making decisions under such conditions. Although there is a broad body of literature on uncertainty, not all of it engages with the question of how, in uncertain scenarios, students' agency can be fostered. Accordingly, this study seeks to address the following research question: how has the literature proposed the promotion of agency in situations and scenarios of uncertainty within the context of science education?

Methodology

To achieve the defined objectives, we conducted a systematic reviews search (Pollock & Berge, 2018) in two databases: ERIC (Educational Resources Information Center) and Web of Science, during the second half of 2024. ERIC is aimed specifically at publications in the field of education, while Web of Science covers a broader spectrum of areas of knowledge. The combination of these two databases allowed for a comprehensive reach, guaranteeing a more detailed and complete review of the topic in the educational context. This method also enabled us to understand how the topic is approached from different perspectives, enriching the analysis and broadening the possibilities for contributions to the field.

In both databases, we used the keywords "uncertainty" and "agency" together, without restricting the period of publication, evaluating all titles and abstracts to identify articles relevant to the scope of the study. In ERIC, we limited the search to "peer review" studies, which resulted in

122 articles, of which 27 were considered relevant. On Web of Science, as it is a broader database, we applied filters to articles in English and within the "Education Educational Research" category, obtaining 133 articles in total. Of these, 31 were relevant, but 11 were already present in the ERIC search, resulting in 20 relevant articles to be added in the base. In all, we came up with 47 articles. We didn't make a specific selection of journals in order to obtain a more robust sample, but one that took into account the selection criteria. For this work, we cut out these 47 articles, analysing only those that fell within the field of science teaching or that investigated central themes of interest to this area (such as climate change, agriculture, *etc.*). As a result, 15 articles were selected and analysed in detail.

Results And Discussion

Table 1. Future-orientated articles in science education.

Title	Authors	Year of Publication	Nature of the article	Journal	Author's institutional country
Facilitating transformative science education through futures thinking	Laherto, A.; Rasa, T.	2022	Theoretical	On the Horizon	Finland
Futurising science education: students' experiences from a course on futures thinking and quantum computing	Rasa, T.; Palmgren, E.; Laherto, A.		Empirical	Instructional Science	
Imagining the School of the Future Through Computational Simulations: Scenarios' Sustainability and Agency as Keywords	Barelli, E			Frontiers in Education	Italy
Making sense of youth futures narratives: Recognition of emerging tensions in students' imagination of the future	Barelli, E; Tasquier, G; Caramaschi, M; Satanassi, S; Fantini, P; Branchetti, L; Levrini, O				
Scientific Literacies for Change Making: Equipping the Young to Tackle Current Societal Challenges	Tasquier, G; Knain, E; Jornet, A				Italy; Norway
Enhancing relevance and authenticity in school science: design of two prototypical activities within the FEDORA project	Cassina, FD; D'Orto, E; Tasquier, G; Fantini, P; Levrini, O	2023			Italy
Quantifying and communicating uncertain climate change hazards in participatory climate change adaptation processes	Müller, L; Döll, P	2024		Geoscience Communication	Germany

Table 2. Articles focusing on scientific uncertainty in science teaching.

Title	Authors	Year of Publication	Nature of the article	Journal	Author's institutional country
Enlisting Supervised Machine Learning in Mapping Scientific Uncertainty Expressed in Food Risk Analysis	Rona-Tas, A.; Cornuéjols, A.; Blanchemanche, S.; Duroy, A.; Martin, C.	2019	Empirical	Sociological Methods & Research	USA; France
Explicit Instruction of Scientific Uncertainty in an Undergraduate Geoscience Field-Based Course	Bateman, K.; Wilson, C.; Williams, R.; Tikoff, B.; Shipley, T.	2022		Science & Education	USA
The glue that makes it hang together: A framework for identifying how metadiscourse facilitates uncertainty navigation during knowledge building discussions	Ko, MLM; Luna, MJ	2023		Journal of Research in Science Teaching	
Course-Based Undergraduate Research Experiences in a Chemical Engineering Laboratory Promote Consequential Agency	Wilson-Fetrow, M.; Svihla, V; Burnside, B.; Datye, A.			Journal of Chemical Education	
Student Uncertainty as a Pedagogical Resource (SUPeR) approach for developing a new era of science literacy: practicing and thinking like a scientist	Chen, Y.; Jordan, M.			Science Activities	
Cultivating a higher level of student agency in collective discussion: teacher strategies to navigate student scientific uncertainty to develop a trajectory of sensemaking	Chen, Y.	2024		International Journal of Science Education	
Navigating student uncertainty for productive struggle: Establishing the importance for and distinguishing types, sources, and desirability of scientific uncertainties	Chen, Y.; Jordan, M.; Park, J.; Starrett, E.		Theoretical	Science Education	

The articles were read in full and some information about them can be seen in Table 1 and 2. Only one of them was published before 2020, which appears to be a timely cut-off, as the COVID-19 pandemic seems to have spurred researchers worldwide to reflect on the issue and propose

interventions in science education. More than half of the articles analysed cite the pandemic in their text, corroborating this trend. What's more, a large proportion of the articles are empirical - around 80% - based on analysing data collected in practical applications in the classroom or analysing educational materials. Although the publications are distributed across several journals, *Frontiers in Education* stands out, hosting ⅓ of the articles, probably due to its focus on global challenges in education, as pointed out in its scope. In addition, 80% of the authors of the articles in this journal are Italian, reflecting an influence from the researchers' country of origin. The other journals are varied, without repetition.

It was noted that there are two macro-trends in the articles analysed. The first is linked to authors from European institutions and focuses on future-oriented education, on the one hand looking exclusively at climate threats and their uncertainties (Müller & Döll, 2024) and, on the other, those that focus on the application of Future Studies in science teaching, as can be seen in Table 1, with many of these studies associated with I SEE and FEDORA project, further corroborating their similarity in focus. If you look at the keywords in the articles, you'll notice that the words “agency” and “future” appear a lot, but this isn't a rule. However, the word ‘uncertainty’ does not appear. These articles use methodological strategies such as the use of narratives, simulations, interdisciplinary practices and others to work with futures and their uncertainties.

The second macro-trend is linked to US authors and is focused on understanding how students deal with scientific uncertainty (conceptual and epistemic) during teaching and learning processes and how they construct knowledge, as can be seen in Table 2. If you look at the keywords in the articles, you'll notice that the word ‘uncertainty’ is the most common and has three forms, while ‘agency’ only appears once. The last article on this list (Ferguson & White, 2023) does not fit into any of these macro-trends, as it brings a theoretical perspective on addressing socio-ecological challenges, in this case climate change, through student action and community involvement.

These macro-trends are not arbitrary; they reflect ways of addressing different types of uncertainty. Studies on scientific uncertainty in the classroom focus on epistemological uncertainty, examining what we know about a subject and how that knowledge is constructed and validated. Such approaches confront the limitations of current knowledge, where uncertainty can be reduced through new data collection or alternative models and theories. Categorising uncertainty types clarifies their distinct origins, characteristics, and implications, helping to determine the most appropriate response. By differentiating them, researchers propose strategies to equip students and educators with critical adaptation and action skills.

Within these studies, agency is understood not merely as an individual capacity to act, but as a sociocultural process through which students assume authority and responsibility both for their own learning and for the collective construction of knowledge within the school community. This perspective distinguishes different levels of agency, contrasting low-level forms, typical of transmissive teaching models, in which students act as passive recipients, with high-level forms, in which learners position themselves as knowledge producers and active participants in scientific practices. In such contexts, agency becomes visible when students identify gaps in their own understanding, formulate guiding questions and collaborate with peers to deepen their comprehension, thereby shifting from a relationship of knowledge consumption to one of authorship and production.

This conception is further expanded through specific forms of agency that emerge in scientific and inquiry-based practices, particularly epistemic and consequential agency. Epistemic agency refers to students’ opportunities to participate meaningfully in knowledge-building practices, contributing to the formulation, evaluation, and direction of investigations, while consequential

agency is expressed through decision-making processes that directly shape the course of work and learning. In learning environments marked by scientific uncertainty, this agency is strengthened, as engagement with the unknown creates conceptual and epistemic demands that motivate action. Agency thus becomes visible not only in students' choices, but also in discursive interactions and in the opportunity, structures afforded by instructional design, especially when students engage in authentic practices and move from peripheral positions towards more central roles within communities of inquiry. In this sense, agency emerges when learners move beyond merely "learning about" science and begin to "figure out how" explanations are produced, mobilising their own ideas, intuitions and experiences to address real-world problems.

Future-orientated work approaches uncertainty in a different way. Although epistemological and epistemic uncertainty are present, arising from the limitations inherent in the methods and frameworks used to think about the future, ontological uncertainty appears to be central. Ontological uncertainty is recognised as inherent to the future, as it involves phenomena that are, by nature, unpredictable, chaotic or emergent. This uncertainty cannot be eliminated, even with perfect information or better models, because it is embedded in reality itself. An example of this is the construction of desirable future scenarios, with the intention of thinking about what, through agency, can be done to reach a desirable future, even if we don't know everything. In this context, the two types of uncertainty are connected in the epistemological reflections on the limits of projections, which can touch on ontological uncertainties, especially when dealing with chaotic or emerging phenomena, with climate change being addressed more than once.

Overall, in this macro-trend, agency is conceptualised as the capacity to intentionally influence and transform social and material worlds, extending beyond a strictly individual notion of action to include shared and collective forms. This conception is strongly grounded in Emirbayer and Mische's framework, in which the projective dimension of agency occupies a central position. By enabling subjects to momentarily disengage from limiting assumptions and to imagine desirable futures guided by values, this dimension underpins educational practices oriented towards futures thinking. In this sense, students are positioned as protagonists capable of constructing pathways of action towards preferable scenarios, shifting from an adaptive stance towards the future to an active and intentional engagement with it.

This understanding of agency is further articulated through models of transformation that integrate personal, practical, and political dimensions, highlighting that action involves connecting values, everyday choices, and broader institutional structures. Agency thus emerges as the capacity to move across these spheres, shifting from a condition of being "objects of change" to that of "subjects of change". In the contexts analysed, science and technology play a fundamental role in this process, particularly through non-deterministic approaches that emphasise the social construction of technology and the role of individuals and collectives in shaping global dynamics. In scenarios marked by uncertainty, agency is understood as the ability to act without guarantees, planning action in relation to multiple possible futures. Strategies such as back casting and the use of complexified narratives reinforce this perspective by framing the future as an open field of possibilities, in which action does not eliminate uncertainty but is constituted precisely through it.

Conclusion

This review identified two main macro-trends in the literature addressing agency and uncertainty in science education, which offer complementary but distinct ways of conceptualising both uncertainty and agency. One macro-trend, largely associated with studies from the United States, focuses on scientific uncertainty within classroom practices, particularly epistemological and epistemic uncertainty arising from the limits of current knowledge. In these studies, uncertainty

is treated as a pedagogical resource, and agency is understood as a sociocultural process through which students assume authority and responsibility for inquiry and knowledge construction. Agency emerges through participation in authentic scientific practices, where epistemic and consequential forms of agency are central: learners identify knowledge gaps, formulate questions, make decisions that shape investigations and collaborate within communities of inquiry. Instructional designs that provide meaningful structures of opportunity are therefore crucial in supporting students' transition from passive reception to active authorship of knowledge.

A second macro-trend, predominantly associated with European research, approaches uncertainty through a future-oriented perspective in which ontological uncertainty occupies a central position. Rather than focusing solely on what is not yet known, these studies recognise uncertainty as an inherent feature of future realities shaped by complex, emergent and unpredictable phenomena, such as climate change. Within this framework, agency is conceptualised as the capacity to intentionally influence and transform social and material worlds, extending beyond individual action to include shared and collective forms. Grounded in the projective dimension of agency, these approaches position students as protagonists capable of imagining desirable futures and constructing pathways of action towards them, even in the absence of certainty.

Taken together, these macro-trends point to the need for science education to integrate epistemological, epistemic and ontological dimensions of uncertainty while foregrounding agency as a central educational outcome. Whether through engagement in knowledge-building practices or through futures-oriented pedagogies, the literature converges on the importance of preparing students to act without guarantees in complex and uncertain contexts. At the same time, the strong geographical concentration of the analysed studies highlights the need for broader contributions from contexts in Latin America, Africa and Asia, where uncertainties may take different forms and educational priorities and resources differ significantly. Expanding this body of research is therefore essential for developing more diverse and globally informed perspectives on agency and uncertainty in science education.

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ESERA 2025 Copenhagen

Expanding Perspectives on Agency within Climate Change Education Debate

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As global challenges intensify, science education is uniquely positioned to bridge knowledge and action by fostering agency in learners. However, traditional approaches often only focus on individual behavioural change, neglecting the collective and political dimensions essential for systemic transformation. This symposium examines the multifaceted nature of agency and its role in empowering learners to navigate the complexities of the Anthropocene through interdisciplinary, transformative education. The symposium integrates insights from environmental psychology, philosophy, futures studies, and science education to explore the idea of collective and political agency as crucial educational outcomes. It highlights three key contributions: a systematic review of the conceptual landscape of agency in climate change education, an interdisciplinary framework that proposes a three-lens model (epistemic, ethical, pragmatic) to conceptualise agency, and an empirical case study applying futures literacy in teacher education to strengthen collective and political agency. By connecting theory and practice, this symposium contributes to the ongoing dialogue about the transformative potential of science education in the context of sustainability and the climate crisis.

Keywords: Agency, Climate change education, Transformative science education

Introduction

Climate change, biodiversity collapse, and socio-environmental injustice increasingly challenge the adequacy of traditional models of science education. In the context of the Anthropocene, education is called upon not only to equip learners with scientific knowledge but also to prepare them to engage meaningfully and responsibly with complex, uncertain, and contested socio-ecological realities (Levrini et al., 2024; Latour, 2018; Sjöström et al., 2018). As such, the concept of *agency* has gained prominence in recent educational discourse. However, it remains far from clear what is meant by *agency* in the context of science education, how it can be fostered, and why it matters.

Although frameworks such as GreenComp (Bianchi et al., 2022) and the PISA 2025 Science Framework (White et al., 2023) conceptualise agency as a multifaceted competence, educational practices, particularly in the context of science education, tend to emphasise individual dimensions, such as behaviour change or personal responsibility. This may limit attention to broader systemic and collective dimensions of agency that are crucial for transformative engagement (Kranz et al., 2025). Particularly in climate change education, the dominant orientation tends to privilege personalised responses and lifestyle choices, while overlooking the more systemic, collective, and political dimensions that underpin the potential for effective social transformation (Kranz et al., 2022; O'Brien, 2015; Otto et al., 2020).

Within the field of science education, the concept of agency is frequently invoked but rarely subjected to rigorous theoretical scrutiny. As highlighted in prior literature (e.g., Marsh et al., 2019; Schubatzky et al., 2026), the concept of agency is often invoked using a variety of related terms, which are not always clearly defined or theoretically distinguished. This contributes to a degree of conceptual ambiguity that may hinder coherence in both research and practice. This lack of clarity risks undermining both research coherence and pedagogical design, as it becomes uncertain which capacities science education is meant to develop and why. At the same time, a growing body of research – initially from social sciences and humanities (e.g. Emirbayer & Mische, 1998) and more recently within science education research - has highlighted the need for a relational collective and political understanding of agency (e.g. Tasquier et al., 2022; Kranz et al., 2022; Levrini et al., 2019). While not entirely new, this view has often remained underdeveloped in science education, particularly in relation to climate change.

Against this backdrop, the ESERA 2025 symposium titled "Expanding perspectives on Agency within Climate Change Education debate" presented aims to advance a theoretically grounded and empirically informed dialogue around the role of climate agency in science education. We argue that science education must not only acknowledge agency as a learning outcome but also expand how agency is conceptualised, operationalised, and supported across curricula, pedagogical practices, and teacher education. More specifically, we contend that collective and political forms of agency, understood as the capacity to act with others to influence structural and systemic conditions, should receive the same attention as the individual dimension, sincethey are essential goals of science education in the Anthropocene (Kranz et al., 2025a).

The symposium brings together three complementary studies that address a shared research problem: *How can science education develop ways to conceptualise, support, and assess agency in light of the scale, complexity, and socio-political nature of the climate crisis?* The first contribution examines this question by mapping how agency is conceptualised in current climate change and sustainability education research, identifying dominant framings and theoretical blind spots. The second contribution develops a theoretical framework that reconceptualises agency through three interrelated lenses, epistemic, ethical, and pragmatic, articulating a normative and multidimensional perspective. The third contribution presents an empirical case study illustrating how futures literacy–oriented pedagogical practices in teacher education can support agentic engagement with uncertain futures and make collective and political dimensions of agency more visible.

Together, these contributions articulate a coherent yet pluralistic effort to reimagine agency beyond individualistic and behavioural paradigms. The symposium thus seeks to strengthen the theoretical foundations of agency in science education while offering practical directions for designing educational experiences capable of fostering the forms of collective engagement and transformative capacity that are urgently needed for a just and sustainable future.

Problematizing The Concept Of Agency In Climate Change Education

In recent years, agency has become a prominent yet theoretically unstable concept in climate change and sustainability education. Across science education research, policy frameworks, and curriculum documents, agency is frequently invoked as a key educational aim, often framed as essential for enabling learners to respond to the climate crisis (White et al., 2023; UNESCO, 2021). However, this growing prominence has not been accompanied by conceptual coherence across different research traditions (e.g., Priestly et al., 2015). Instead, agency is used in markedly different ways, ranging from psychological readiness and pro-environmental behaviour to civic participation and action.

The first contribution to this symposium addresses this problem through a systematic scoping review of agency in climate change and sustainability education research. Analysing 110 peer-reviewed studies published between 2004 and 2024, the review maps how agency is defined, theorised, and operationalised in school-level science education. A central finding is the widespread absence of explicit definitions: fewer than one third of the reviewed studies provide a clear theoretical definition of agency, while the majority use the term implicitly or without clarification. This pattern exemplifies what Marsh et al. (2019) describe as a jingle–jangle fallacy, where the same label refers to different constructs, or different labels describe overlapping phenomena.

This lack of definitional clarity has concrete consequences. Studies labelled as fostering "agency" often pursue fundamentally different educational goals: some focus on strengthening students' hope, motivation, or self-efficacy; others aim at developing sustainability-related competencies; still others foreground participation, identity work, or civic engagement. Without explicit conceptual positioning, it remains unclear which forms of agency are being aimed to be supported, how they relate to one another, and which are adequate for addressing the systemic and political nature of the climate crisis. From a pedagogical perspective, one might argue that this diversity is of secondary importance, as the central concern of climate change education is to support students in doing something in the face of the climate crisis, rather than remaining passive or disengaged. In this sense, different pathways to agency may appear equally legitimate.

However, precisely because agency is increasingly framed as a key educational response to a systemic and political crisis, it is not trivial which forms of agency are being promoted. Without explicit conceptual positioning, there is a risk that agency becomes reduced to individual coping, lifestyle choices, or isolated actions, thereby obscuring questions of collective responsibility, power, and structural change. Clarifying how agency is conceptualised is therefore not a purely theoretical concern, but a prerequisite for aligning educational aims with the transformative demands of the climate crisis.

To bring analytical structure into this fragmented landscape, the review identifies five recurring conceptualisations of agency in the literature. These include (1) agency as a psychological resource, emphasising hope, self-efficacy, and emotional resilience; (2) agency as competence, framing agency as a set of learnable and assessable knowledge–skill–attitude configurations aligned with policy frameworks such as PISA 2025; (3) critical-emancipatory agency, rooted in Freirean and critical science education traditions, foregrounding empowerment, justice, and collective struggle; (4) temporally embedded sociocultural agency, highlighting identity, participation, and the integration of past experiences and imagined futures; and (5) action-oriented or problem-solving agency, focusing on concrete participation and locally situated sustainability actions.

Importantly, these conceptualisations are not mutually exclusive. Rather, they emphasise different clusters of attributes and rest on distinct theoretical traditions. The review therefore proposes conceptualising agency as a family resemblance concept (Podsakoff et al., 2016), characterised by overlapping features rather than a single defining essence. Across traditions, several central attributes recur, including a perceived capacity to act, situatedness in socio-cultural contexts, participation with others, and a future-oriented perspective. At the same time, each conceptualisation foregrounds distinctive elements—such as psychological resources, competencies, empowerment, identity work, or local problem-solving—that shape how agency is enacted and studied.

This diagnosis sets the stage for the subsequent contributions in the symposium. Building on the conceptual mapping provided by the review, the second contribution advances an

interdisciplinary framework that reframes agency through epistemic, ethical, and pragmatic lenses. The third contribution presents an empirical case study illustrating the role of futures literacy in shaping agency-related orientations in teacher education, including collective and political dimensions of agency. Together, these contributions respond to the conceptual challenges identified here by moving beyond individualistic and behavioural paradigms toward a more robust understanding of agency suited to science education in the Anthropocene.

Reframing Agency Through Interdisciplinary Perspectives

Building on the need for greater conceptual clarity, the second contribution proposes a theoretical framework that redefines agency as a multidimensional educational construct. Tasquier, Pongiglione, and Ricci (2026) argue that science education must be expanded through the integration of insights from philosophy and economics to address the ethical, epistemic, and pragmatic dimensions of agency.

Their model, developed in the context of the ENCOMPASS research programme, moves beyond conventional notions of agency as primarily psychological or behavioural. It aims to capture the complex and situated nature of agency as it manifests in the climate crisis, where action must often be taken despite uncertainty, structural constraints, and conflicting values. Through a theoretically grounded synthesis of three disciplinary perspectives - science education, philosophy, and economics - the model proposes an educational response that recognises the plurality and interdependence of the competencies required for transformative engagement (Tasquier et al. 2026; Sezen-Barrie et al., 2026).

Central to this model is the articulation of three interwoven lenses through which agency can be rethought. First, epistemic-driven agency refers to the capacity to critically engage with scientific knowledge. In the context of climate science, this entails grappling with complex systems, probabilistic models, and the provisional nature of evidence. Students must be able to navigate contested knowledge claims, evaluate the reliability of sources, and understand how scientific knowledge interacts with political and social interests. This epistemic engagement is essential to avoid both naïve scientism and paralysing relativism.

Second, ethical-reflective agency foregrounds the importance of moral reasoning in contexts characterised by uncertainty and normative pluralism. Climate change raises profound ethical questions about responsibility, justice, and intergenerational equity. Philosophical reflection offers tools for deliberating about what is at stake, for whom, and according to which values. By integrating ethical reflection into science education, learners are not merely trained to know or to act but to judge. This form of agency requires sensitivity to others, awareness of ethical complexity, and the capacity to live with ambiguity.

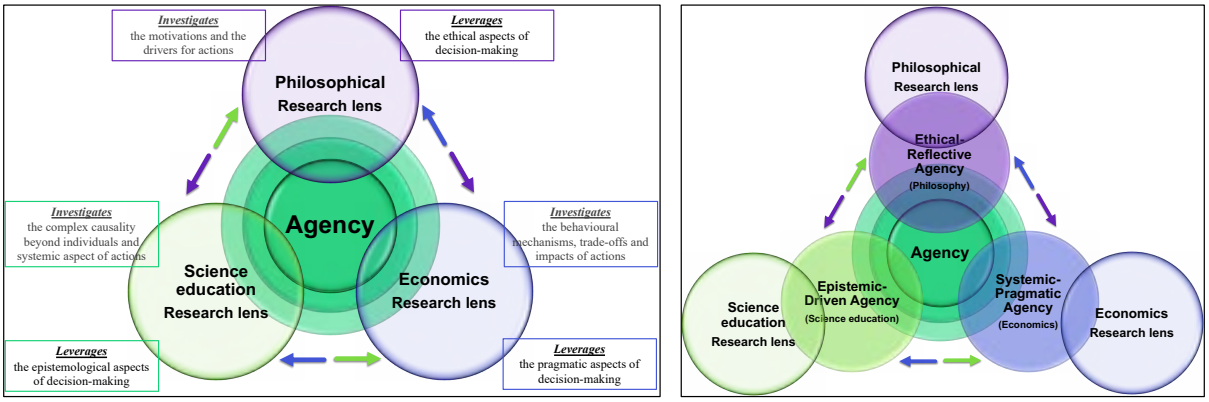
Third, systemic-pragmatic agency refers to the ability to understand and act within real-world constraints, considering trade-offs, opportunity costs, and institutional limitations. Drawing on economic reasoning, this dimension of agency attends to the feasibility and effectiveness of climate actions. Students are invited to think strategically, acknowledging that ideal solutions may not always be viable and that action requires negotiation and compromise. Systemic-pragmatic agency thus aligns action with context, enabling learners to move from aspiration to implementation.

Taken together, these lenses offer a reframing of agency as a distributed and educable capacity. Rather than treating agency as a fixed trait or an individualised outcome, the framework situates it within learning environments that scaffold deliberation, judgement, and action. It calls for science education to be reimagined as a site of public reasoning, where students engage not only with scientific content but with the socio-political and ethical dimensions of science-in-society.

This perspective resonates with Vision III of scientific literacy (Sjöström et al., 2017), which advocates for the development of critical and transformative competencies that enable students to participate in shaping more just and sustainable futures. It challenges the epistemological reductionism of traditional curricula and calls for an expansion of educational aims to include the cultivation of political imagination, collective responsibility, and civic engagement.

Importantly, the framework is not merely theoretical. It has informed the development of design principles that guide the creation of pedagogical environments where these forms of agency can emerge (Sezen-Barrie et al., 2025). These environments are characterised by exposure to uncertainty, authentic problem contexts, deliberative dialogue, and opportunities for situated action. They invite students to encounter complexity not as a barrier but as a condition of responsible engagement. By positioning agency at the intersection of epistemic, ethical, and pragmatic reasoning, this contribution offers a powerful vision for rethinking science education in the Anthropocene.

Figure 1. *ENCOMPASS Three-Lens Model of Climate Agency. (Adapted from Tasquier, Pongiglione & Ricci, 2026).*



Futures Literacy And Agency In Teacher Education

The third contribution examined how futures literacy is related to the development of agency in the climate crisis, with a particular focus on pre-service teachers (PSTs). In contrast to the conceptual plurality highlighted in the other symposium contributions, this study deliberately adopts an explicit working definition of agency to enable empirical analysis. Here, agency is understood as the capacity for autonomous social action through which individuals intentionally transform their social and material worlds (e.g., Biesta & Tedder, 2007). It is further viewed as inherently future-oriented, as people's anticipations and visions of the future shape how they act in the present (Lombardo, 2016; Ojala, 2012).

Two interrelated conditions described in the literature motivated this focus. First, research on young people's future thinking points to a lack of constructive future perspectives, often characterised by dystopian and fixed visions of the future (e.g., Miller, 2018). Second, studies in science education on climate change suggest that educational approaches frequently remain passive with regard to agency, prioritising individual agency or knowledge acquisition rather than fostering learners' capacities to shape social and material conditions (Kranz et al., 2022; Kranz, 2024), including collective and political forms of agency. Together, these patterns risk constraining both how the future is imagined and how agency is perceived. This gap is particularly consequential in teacher education as PSTs can be understood as future change agents whose own sense of agency and future imaginaries are likely to shape how they later engage students with the climate crisis (Winter et al., 2022). Yet, there is still limited research on how science teacher education can deliberately support the development of futures literacy and agency. Building on these motivations, the contribution addresses the guiding question of how a

climate-focused intervention can support the development of agentic, sustainability-oriented future thinking in PSTs. To this end, an interdisciplinary teaching module named (*FULit - Shaping the Future in Times of the Climate Crisis*) was implemented in the physics teacher programme at Freie Universität Berlin (Germany), integrating futures studies methods with transformative action-oriented approaches (Kranz et al, 2025b). The study involved 15 PSTs and followed an exploratory qualitative pre–post design. Focusing, among other data sources, on patterns in PSTs' future narratives, the analysis was structured along three dimensions: (1) the perceived quality of the future, (2) the perceived agency to shape the future, and (3) sustainability-related agency.

Regarding the perceived quality of the future, pre-intervention future narratives were predominantly articulated as ambiguous and uncertain. Rather than clearly dystopian or utopian visions, many accounts emphasised uncertainty, for example with respect to how climate change might develop or how societal responses could unfold. Dystopian elements were present but did not dominate, while utopian visions were rare. Post-intervention analyses indicate a slight shift: dystopian future visions declined, while ambiguous and uncertain futures became more prominent. The prevalence of ambiguity did not decrease and explicitly utopian futures remained rare.

With regard to the perceived agency to shape the future, pre-intervention narratives were equally distributed between active and passive orientations. Following the intervention, a slight shift toward agentic framings was observed (e.g., *'We redesign school life'*), more often positioning participants as potential actors capable of contributing to change. This shift was particularly visible in the combination of ambiguous future scenarios with agentic orientations. In contrast, utopian futures, when present, were more often paired with passive framings, indicating that positive visions did not necessarily coincide with a stronger sense of agency.

Finally, analysis informed by the EU GreenComp framework showed additional qualitative changes. Post-intervention narratives more frequently articulated, for example, acting for sustainability. While references to collective action remained rare, political agency became more visible. Participants more often framed the climate crisis as a socio-political challenge and referred to systemic or policy-related solutions rather than exclusively to individual behaviour.

Overall, the findings suggest that futures-oriented, transformative approaches hold the potential to support agentic engagement under uncertainty in the context of the climate crisis. Participants' future visions remained largely ambiguous rather than optimistic but were more frequently paired with agentic orientations. This pattern may be interpreted as a form of constructive hope (Ojala, 2012), oriented toward navigating uncertainty and reflecting on multiple possible futures rather than striving for idealised outcomes. The study followed an exploratory qualitative approach focused on identifying patterns rather than assessing intervention effectiveness. It examined prerequisites of agency, such as future imaginaries and perceived possibilities for action, rather than agency as an outcome per se. The findings point to the need for more structured opportunities for collective action and inform future comparative and longitudinal research on how different pedagogical elements support distinct dimensions of agency.

Discussion

Together, the three contributions in this symposium articulate a coherent and multilayered response to the central research problem: How can science education conceptualise, support, and assess forms of agency that are adequate to the scale, complexity, and socio-political nature of the climate crisis? Each study illuminates distinct facets of this problem, yet they also converge

in affirming the need for a paradigmatic shift in how agency is understood and cultivated within science education.

The first contribution offers a panoramic diagnosis of the current conceptual landscape, highlighting the conceptual fragmentation and the risk of a dominance of individualistic framings in empirical research. This mapping underscores the importance of developing and using theoretically robust and pedagogically meaningful definitions of agency that transcend behavioural models and foreground relational, collective, and political dimensions. It provides the groundwork for understanding why existing approaches often fall short in addressing the systemic nature of the climate crisis.

The second contribution builds on this diagnosis by offering an interdisciplinary model that reconceptualises agency through epistemic, ethical, and pragmatic lenses. Rather than viewing agency as a static competence, it frames it as a dynamic and educable process embedded in deliberation, judgement, and strategic action. This model provides a normative vision of what agency *should* entail in the context of climate change, anchoring educational goals in democratic reasoning, moral complexity, and institutional awareness. Crucially, it affirms that science education must not only transmit knowledge but also scaffolded forms of agency that enable learners to navigate and shape contested socio-ecological futures.

The third contribution translates this vision into pedagogical practice through the integration of futures literacy into teacher education. It offers an empirical illustration of how futures-oriented educational approaches can be associated with shifts in learners' future imaginaries and perceived agency, including greater attention to collective and political dimensions of climate action. In doing so, it illustrates the pedagogical viability of the theoretical claims advanced in the second contribution. Taken together, the three studies advance the proposition that science education must be reoriented to explicitly cultivate agency not only as individual agency but also as a collective and political practice. Addressing agency in science education therefore requires conceptual clarity about which forms of agency are being invoked (Contribution 1), a theoretical reframing of agency as an epistemic, ethical, and pragmatic educational capacity (Contribution 2), and an empirical illustration of how these conceptual insights can be taken up in futures-oriented pedagogical practice (Contribution 3). Rather than being treated primarily as a by-product of knowledge acquisition or an individual trait, agency can be conceptualized as a central educational aim that is intentionally designed for. The three contributions in this symposium do take important steps to contribute to this aim. Rather than prescribing a singular model of agency, they point to the need for science education to become a space where different forms of agency can be recognised, interrogated, and deliberately cultivated, through research, curriculum design, and teacher education. This, we argue, is essential if science education aims to play a meaningful role in shaping responses to the climate crisis.

Conclusion And Outlook

This symposium contributes to an emerging educational discourse that seeks to reimagine science education as a site for cultivating transformative forms of agency. By interrogating how agency is defined, theorised, and enacted, the three contributions collectively make the case for a shift away from narrow, behavioural models toward more expansive and politically engaged framings. They argue for the design of educational environments where students are equipped to challenge, critique, and change the conditions that produce it.

Importantly, the symposium also points forward. It lays the conceptual and empirical foundations for future research and innovation in science education, particularly in the context of the newly funded EU Erasmus+ project TRACE (Transformative Agency in Climate Education),

coordinated by the University of Innsbruck. TRACE builds directly on the theoretical and pedagogical advances discussed in this symposium, aiming to foster teachers' capacity to design and implement climate education that cultivates collective and political agency. Through a transdisciplinary, practice-based approach, TRACE focuses on supporting students and teachers in exploring how collective and political dimensions of agency can be addressed through climate education. It does so by involving them in the design and implementation of teaching scenarios that integrate other perspectives beyond science education, while also developing tools for self-reflection in regard to agency in the climate crisis.

The work presented here thus represents both a reflection on current limitations and an invitation to envision what science education towards agency could become in the Anthropocene. It affirms that agency is not a peripheral theme but a central challenge, one that demands conceptual precision, interdisciplinary imagination, and pedagogical innovation. Responding to this challenge means creating educational spaces where science is not merely learned but lived, where learners become co-authors of their futures, capable of engaging with complexity not with resignation, but with constructive hope and collective intent.

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Part 10 / Strand 10

Environment, Health And Science Education

Co-editors: *Sarah Haines & Benedikt Heuckmann*

Part 10 / Strand 10 Environment, Health And Science Education

Theories, methods, and practices about environmental, ecological, earth, health, and medicine education. Includes debate about literacies and approaches related to the environment, including indigenous perspectives and connection with more comprehensive aspects of justice as well as planetary well-being, and the design, development, and evaluation of the impact of programmes and experiences.

Sub-themes:

1) Environmental Literacy and Science Education
2) Health and Medicine Education
3) Indigenous Perspectives on Environmental Education
4) Justice and Equity in Environmental Science Education

Contents

Strand 10: Environment, Health, And Science Education – Exploring Teachers' And Learners' Conceptions, Competence, And Agency In Times Of Environmental And Health Challenges875

Section: Climate Change Education And The Climate Crisis 877

Alternative Conceptions About The Greenhouse Effect: An Analysis Across Educational Stages 878

Assessing Climate-Change Competence in Pre-Service Teachers: Knowledge, Attitudes, and Behavioural Engagement in Climate Education 886

Students' Misconceptions About Heatwaves And Their Interconnection With Climate Change 892

First Approaching To Preservice And Inservice Teachers Conceptions About Groundwater .. 899

Pre-Service Teachers' Behaviours Toward Environmental Problems 904

Studying Students' Reasoning About The Ozone Layer Depletion In The Context Of Argumentation 909

Action Research On Climate Change Education In Lower Secondary School – Students' And Teachers' Experiences 916

Section: Transformative Learning In Environmental Education 921

Fostering Environmental Science Competencies In The Anthropocene: Implementation Of The Four-Step AAAR Learning Cycle Using PISA 2025 Framework 922

Developing Environmental Competencies And Identities Through A Trans-Contextualization Learning Process Using Socio-Scientific Issues 933

Section: Getting Engaged With Nature And Environment 943

Children's Connection to Nature: Do Forest Schools Make a Difference? 944

Empowering Pupils To Explore Urban Environments. Identifying Contexts For Environmental Sensing Using Non-Functional Prototyping. 950

Section: Sex Education, Equality, And Menstruation 960

Learning About The Menstrual Cycle Through The Use Of Narratives In Initial Teacher Education 961

Exploring Adolescent Student's Knowledge and Beliefs about Menstruation and Understanding the Influence of Education on It. 966

Section: Health Conceptions In Social Media 974

Exploring Expert Conceptualizations Of Type-2 Diabetes Through Network Analysis: A Pilot Study 975

ESERA 2025 Copenhagen

Strand 10: Environment, Health, And Science Education – Exploring Teachers' And Learners' Conceptions, Competence, And Agency In Times Of Environmental And Health Challenges

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Strand 10 of the ESERA conference focuses on the intersections of environment, health, and science education, bringing together research that examines how learners and teachers engage with scientific ideas closely connected to individual well-being, societal challenges, and environmental sustainability. Research in this strand addresses pressing issues such as climate change, environmental degradation, and health-related socioscientific issues, while also exploring the pedagogical, conceptual, and affective dimensions of teaching and learning science in these contexts. The papers in this chapter reflect the breadth of work within Strand 10, with a strong emphasis on learners' and teachers' conceptions of environmental and health-related phenomena. Contributions were organized into five subsections, namely, "Climate Change Education and the Climate Crisis", "Transformative Learning in Environmental Education", "Getting Engaged with Nature and Environment", "Sex Education, Equality, and Menstruation", and "Health Conceptions in Social Media".

Most contributions investigate learners' and teachers' understandings and competencies related to environmental topics, including the greenhouse effect, groundwater systems, climate change, and the ozone layer, examining both scientifically accurate conceptions and persistent misconceptions among students and preservice teachers. Together, these studies highlight the complexity of climate science learning and the need for instructional approaches that explicitly attend to systems thinking, uncertainty, and human influences on environmental processes as well as addressing obstacles to integrative, action-competence-oriented climate education. Related papers extend this focus on conceptual understanding to other environmental and health topics, including menstruation and metabolic disease. These contributions illustrate how scientific knowledge in environmental and health domains is intertwined with everyday experiences, cultural norms, and personal relevance. By analysing learners' and teachers' existing ideas, these studies provide insights into challenges for teaching conceptually demanding and socially sensitive topics in science classrooms.

Beyond conceptual knowledge, several papers address environmental competencies, action-oriented education, behaviours, and dispositions. Research on children's connection to nature and preservice teachers' environmental behaviours foregrounds affective and ethical dimensions of science education, emphasizing the importance of fostering responsibility, care, and engagement alongside scientific understanding. Studies examining climate change competence similarly adopt a broader perspective on learning, focusing on the integration of knowledge, skills, and attitudes necessary for thoughtful participation in societal decision-making. Studies on health conceptions argue for inclusive education that addresses stigma and fosters gender equity. A related contribution examines how health knowledge is conceptualized and communicated through digital and social media sources.

Pedagogical design is another key theme across the chapter. Contributions examining the use of learning cycles in high school environmental education and students' development of prototype environmental sensors highlight inquiry-based and design-oriented approaches that actively engage learners in scientific practices. These studies also point to the potential of digital tools and hands-on technologies for supporting data-informed reasoning and deeper engagement with environmental issues.

A notable trend across the chapter is the central role of teacher education. Multiple papers focus on preservice teachers' conceptions, competencies, instructional practices, and behaviours related to environment and health, underscoring the importance of teacher preparation for addressing socioscientific issues in meaningful ways. A second trend is the field's movement toward competency-based and action-oriented frameworks that integrate knowledge, skills, values, and agency. Third, questions of equity — relating to gender, culture, and social justice — recur across subsections, reflecting a broader understanding of what science education in these domains is for. In this regard, these studies highlight both opportunities and tensions in supporting future teachers as they navigate curricular expectations, scientific complexity, and societal relevance.

Positioned within the wider field of science education research, the work in this strand contributes to ongoing debates about the purposes of science education in the context of global environmental change and public health challenges. The papers advance conceptions of scientific literacy that extend beyond content mastery to include critical thinking, ethical awareness, and agency. In doing so, they align closely with the conference themes of sustainability and digital advances, illustrating how environment and health education can support learners in engaging with complex challenges that will shape present and future societies.

Section: Climate Change Education And The Climate Crisis

Alternative Conceptions About The Greenhouse Effect: An Analysis Across Educational Stages

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This study analyses alternative conceptions of the greenhouse effect among high school and postgraduate participants. To this end, responses to an open-ended questionnaire were qualitatively evaluated, using as the analytic instrument one dimension of a construct map developed within a broader study to explore students' initial ideas about the regulation of the planet's climate. The sample comprised 131 participants, divided into two groups: Middle school, high school students, and postgraduate students and active teachers. The findings show that, although educational level influences the level of technical detail in the responses, alternative conceptions persist across all levels. The most frequent include identifying the greenhouse effect as part of the ozone layer, equating it with climate change, and failing to acknowledge its regulatory role in the Earth's climate system. While this latter difficulty is more evident at initial stages, it also appears at advanced levels, underscoring the need to implement targeted teaching, learning strategies that explicitly address these alternative conceptions across all educational stages.

Keywords: Greenhouse effect, alternative conceptions, persistent ideas.

Introduction

Science education plays a pivotal role in shaping an informed citizenry capable of making evidence-based decisions regarding contemporary environmental challenges such as climate change. A sound understanding of the factors that regulate the climate is essential for students, from primary education through university, to develop a critical perspective on human influence on the environment (Morote et al., 2021). Indeed, UNESCO (2021) emphasizes the importance of integrating climate knowledge into school curricula, noting that a deep understanding of these issues is crucial for future citizens.

Nonetheless, numerous learning difficulties persist regarding the regulation of the Earth's climate and its regulatory factors. In particular, a recurrent difficulty is the alternative conception that the ozone layer is a climatic regulator or forms part of the greenhouse effect. This idea often arises from its confused treatment in textbooks (Sakarya et al., 2023), where explanations of these two atmospheric phenomena are insufficiently differentiated, the terminology is complex, and both elements are intrinsically challenging to grasp (Andersson & Wallin, 2000).

This study therefore aims to analyse participants' conceptions of the greenhouse effect across different educational stages, and thus their persistence, with a view to informing future instructional designs that help students overcome these learning difficulties.

Background

In the field of science education, didactic transposition adapts complex phenomena to make them more accessible to students, aligning with their cognitive capacities and supporting progression (Adúriz-Bravo, 2009). In this study, we define the school-science idea of the greenhouse effect

as the atmospheric process of absorption and re-emission of infrared radiation, explicitly highlighting its positive nature as a regulatory factor of the climate, essential for life.

A range of studies has examined the ideas that students and teachers hold about atmospheric phenomena and components. Papadimitriou (2004) investigated prospective primary teachers' conceptions of climate change, the greenhouse effect, and the ozone layer using open-ended questionnaires. The study concluded that most of these preservice teachers struggled to differentiate among these concepts. For example, they believed that the ozone hole is directly related to global warming or that gases in the ozone layer contribute to the greenhouse effect. Along similar lines, though focused exclusively on the greenhouse effect, Sakarya et al. (2023), using open-ended questionnaires, found that students in a Master's program in Environmental Education maintained alternative conceptions about this phenomenon, showing difficulties in understanding the role of atmospheric gases involved and the physical mechanisms underlying the retention of terrestrial heat.

These findings underscore the need to explore new instructional approaches that can help overcome such learning difficulties. In this regard, model-based teaching is conceived as a comprehensive didactic approach in which the teacher structures learning around activities that foster deep understanding and critical thinking, thereby enabling more accurate and reflective explanations of the phenomenon (Oliva, 2019).

This strategy rests on the idea that school models function as representations mediating between learners and scientific knowledge, whose relationship to phenomena is one of similarity rather than exact reproduction of reality (Adúriz-Bravo, 2009). From a semantic view of theories, a theoretical model may take multiple forms, diagrams, tables, physical mock-ups, or drawings, provided it serves to describe, explain, and predict the phenomenon under study (Oliva, 2019).

This approach is particularly powerful in school contexts because it enables work with progressively more complex models that are close to students' initial ideas yet oriented toward more rigorous explanations. Thus, instruction is organized around cycles of model construction, comparison, revision, and application, rather than the transmission of closed definitions (Soto & Couso, 2023). In this sense, structuring learning around models offers a plausible pathway to re-channel alternative conceptions without dismissing them, integrating them instead as a starting point within conceptual progression trajectories (Oliva, 2019).

Analogies play a prominent role within model-based teaching because they help students imagine, visualize, and reason about unobservable entities and complex processes, and they support the organization of knowledge through provisional versions of the model prior to application (Harrison & Treagust, 2006; Jorba & Sanmartí, 1996). However, their effectiveness depends on the teacher's guidance, explicit or otherwise, in helping students recognize both the similarities and the limitations between the analogy and the target phenomenon (Harrison & Treagust, 2006). For the greenhouse effect, carefully designed analogies can anchor core ideas such as radiative balance, absorption/reflection, and its natural regulatory role in maintaining the planet's temperature (Eriksson et al., 2024).

Methodology

Participants

A total of 131 participants residing in the province of Cádiz (Spain) took part in this study: 74 students in 3rd and 4th grades of middle school, 11 students in 1st grade of high school, 39 Master's students (8 from the Master's in Aquaculture and Fisheries, and 31 from the Master of Education), and, finally, 7 in-service teachers at the high school, and university levels.

To explore the presence and persistence of alternative conceptions across educational stages, participants were grouped into two cohorts: Group 1 comprised the 85 middle and high school student participants, and Group 2 comprised the 46 university-level participants (Master's students and practicing teachers). This study forms part of a broader research project aimed at designing, implementing, and evaluating a teaching–learning sequence on the regulation of the planet's climate. In this phase, the analysis focuses on validating a construct map; consequently, the groups were not balanced a priori in the initial design. The configuration of this particular study was established post hoc, once the data had been analysed and the persistent ideas to be characterized in greater depth had been identified.

Instrument

A validated open-ended questionnaire (Brenes-Cuevas et al., 2024) was used as the data collection instrument, consisting of four questions. These questions were designed to address different factors regulating the Earth's climate, such as global ocean circulation, atmospheric circulation, and the greenhouse effect. The present study focused exclusively on the question related to the greenhouse effect: *"What is the greenhouse effect? Why does it occur? Explain it in your own words and represent it using the following diagram."*

Data Analysis Procedure

A construct map was developed and validated to analyse the responses related to each of the factors regulating climate. However, as previously mentioned, the present study focuses specifically on one of the dimensions of this construct map, that corresponding to the greenhouse effect (Table 1).

To address the aim of this study, analysing participants' conceptions of the greenhouse effect, a three-phase analytical procedure was applied. In the first phase, responses were classified according to the levels defined in the construct map (Table 1), with the objective of identifying the overall frequency distribution.

Table 1. Greenhouse effect dimension of the construct map.

LEVEL 1	LEVEL 2	LEVEL 3	LEVEL 3
Trivial or blank responses.	Identifies the greenhouse effect as a phenomenon occurring in the atmosphere, possibly mentioning the absorption and/or reflection of solar radiation. Does not clearly define the process and/or interprets it as synonymous with other phenomena (climate change, ozone layer, etc.). Makes no reference to its nature (neither as a natural phenomenon regulating the climate nor as an anthropogenic factor).	Identifies the greenhouse effect as the phenomenon of absorption and/or reflection of solar radiation in the atmosphere, without reference to other phenomena (climate change, ozone layer, etc.), but does not clearly define the process. Makes no reference to its nature (as a natural phenomenon regulating the climate), or attributes it exclusively to anthropogenic factors with negative consequences for the planet.	Identifies the greenhouse effect as the phenomenon of absorption and reflection of solar radiation in the atmosphere, possibly without clearly defining the process. Refers to its positive nature as a regulatory factor of the climate, potentially recognizing it as an essential factor for life.

Subsequently, in the second phase, the set of responses corresponding to participants classified at Level 2 was analysed in greater detail. An emergent system of non-exclusive categories was established to characterize the responses and examine frequency distributions, given the high number of participants identified at this level, as will be discussed in the following section. The resulting categories were:

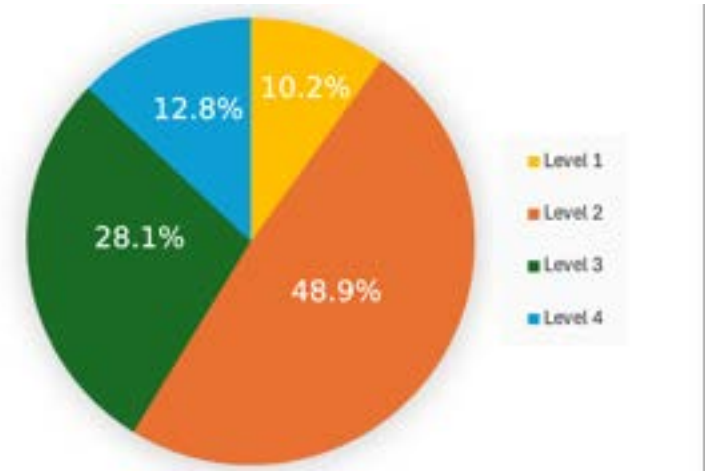
- Atmospheric phenomenon: Participants identify the greenhouse effect as a phenomenon that occurs in the atmosphere.
- Phenomenon functioning: Participants mention the absorption and/or reflection of solar radiation.
- Nature of the phenomenon: Participants identify the greenhouse effect as either a natural or an anthropogenic phenomenon.
- Ozone layer: Participants associate the ozone layer as part of the greenhouse effect.
- Climate change: Participants identify the greenhouse effect as synonymous with climate change.
- Other: This category includes other low-frequency alternative conceptions that are not trivial enough to be classified under Level 1.

Finally, in the third phase, the frequency of these categories was compared between the two groups of participants classified at Level 2, differentiated by educational level: Group 1 (middle and high school students) and Group 2 (participants with university studies). The aim was to analyse the persistence of alternative conceptions across educational stages.

Results And Discussion

Following the established sequence of analysis, the first phase consisted of classifying the responses about the greenhouse effect according to the levels defined in the construct map (Table 1). The analysis revealed a distribution of participants' ideas across all levels (Figure 1), showing a similar percentage (around 10%) at Levels 1 and 4. However, the most representative level was Level 2, accounting for 48.9% (64 out of 131 participants). These participants understood the greenhouse effect as a phenomenon occurring in the atmosphere but did not clearly define the process and/or interpreted it as synonymous with other phenomena, such as climate change or the ozone layer, without referring to its nature. For this reason, Phase 2 of this study focuses on the distribution and categorization of these ideas.

Fig. 1. Distribution by levels of participants' responses about the greenhouse effect.



In the second phase of the study, the responses of the 64 participants classified at Level 2 were analysed in detail according to the categorization described in the previous section. The results show, first, that 93.8% of the participants at this level (60 out of 64) identified the greenhouse effect as an atmospheric phenomenon. However, this identification was not always accompanied by complete explanations of how the phenomenon operates (Figure 2).

Figure. 2. Example of a participant's representation at Level 2.

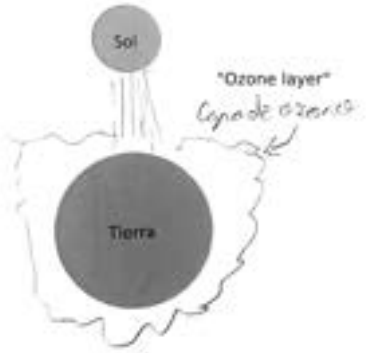
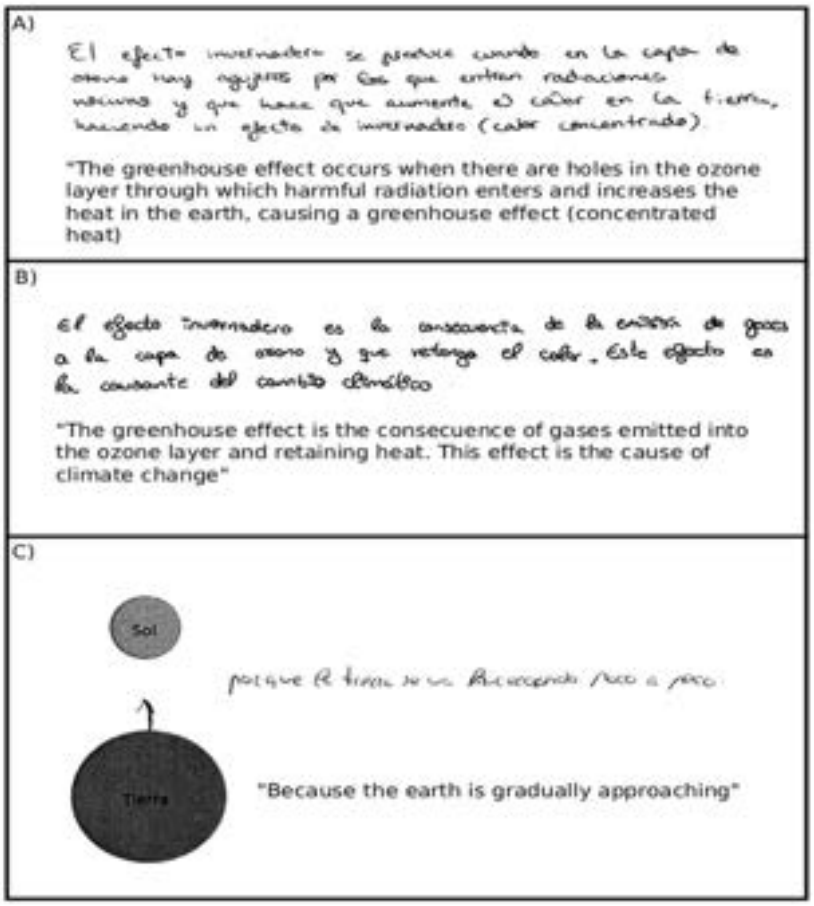


Figure. 3. Example of Level 2 participants' responses classified into different categories. a) Ozone layer, b) Climate change, and c) Other.



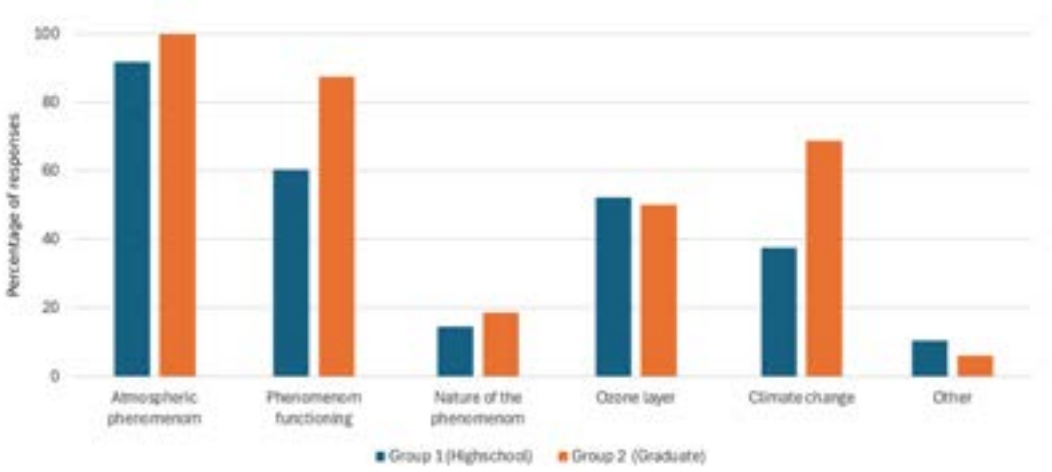
Regarding the functioning of the phenomenon, 67.2% of participants (43 out of 64) mentioned that the greenhouse effect involves the absorption and/or reflection of solar radiation. Despite this, it is noteworthy that the category "Nature of the phenomenon" shows an absence of reference to the natural character of the greenhouse effect in 54 out of 64 participants (84.4%). Likewise, in the "Ozone layer" category, 33 participants (51.6%) associated this element as part of the greenhouse effect. Finally, confusion between the greenhouse effect and climate change was

observed in 23 responses (35.9%), while 6 of the 64 participants (9.4%) provided answers included in the "Other" category (Figure 3).

Finally, in the third phase of the analysis, with the aim of examining the persistence of alternative conceptions across different educational stages, the responses of participants classified at Level 2 of the construct map from the previous phase were separated according to their educational level. The first group consisted of middle and high school students, while the second group included participants with university studies. The frequencies obtained for each category were compared between the two groups.

Figure 4 presents the results of this analysis. It can be observed that all university-level participants (100%) (Group 2) identified the greenhouse effect as an atmospheric phenomenon without clearly defining the process, which is why they are placed at Level 2 of the construct map. Similarly, although with a slightly lower percentage (91.6%), middle and high school student participants (Group 1) also mentioned this category at this level.

Fig. 4. Percentage of responses according to the Level 2 categorization for both participant groups. Non-exclusive categories.



Furthermore, 88% of Group 2 participants mentioned that the greenhouse effect involves the absorption and/or reflection of solar radiation, while only 60% of Group 1 participants expressed this idea. This suggests a greater ability to describe specific physical aspects of the phenomenon at more advanced educational stages, which seems logical given their training. However, both groups showed similar percentages of responses that did not reflect an understanding of the nature of the phenomenon, 85.4% in Group 1 and 81.3% in Group 2. In other words, only 14.6% and 18.7%, respectively, identified the greenhouse effect as a natural or anthropogenic phenomenon, revealing an incomplete understanding of the phenomenon at both educational levels.

Regarding alternative ideas, the results show that a similar percentage of participants in both groups considered the ozone layer to be part of the greenhouse effect, 52% in Group 1 and 50% in Group 2. These findings suggest that this alternative conception persists even at advanced educational stages. However, confusion between climate change and the greenhouse effect was more prevalent among university students (68.8%) than among middle and high school students (37.5%). This finding highlights the complexity that university-level participants face when differentiating between related climatic phenomena or elements, despite their advanced education. It also shows that, while alternative conceptions are present in both groups, the characteristics of each educational stage influence the type of ideas expressed.

In the case of university students, this tendency may be explained by deeper but fragmented knowledge, which allows them to recognize the relationship between the greenhouse effect and

climate change. However, they fail to clearly distinguish the nature of the former as a natural phenomenon, in contrast to the anthropogenic increase in greenhouse gases that intensifies this effect and contributes to climate change. This partial understanding may lead to associations with other atmospheric elements, such as the ozone layer (Roßbegalle & Ralle, 2016). Conversely, middle and high school students, having less structured knowledge, tend to provide simpler and shorter explanations, which reduces associations between phenomena, although this does not imply stronger understanding, but rather lower conceptual complexity (Shepardson et al., 2011).

Alternative conceptions related to the ozone layer and climate change persist over time, consistent with the findings of Sakarya et al. (2023), who conducted a study with Master's students in Environmental Education. This pattern of alternative conceptions across different educational stages confirms the need for model-based teaching that promotes the integration and articulation of the various atmospheric phenomena and components.

In order to improve educational practice and in line with the results obtained, it is proposed to integrate analogies within model-based teaching–learning sequences to facilitate the shift toward Level 3 or 4 explanations, in which students cease to associate these phenomena indiscriminately and begin to recognize the greenhouse effect as a natural process regulating the climate. Analogies, by involving the comparison between elements of the target phenomenon and those of the model, make it possible to identify both the similarities and the differences between them. This comparative process helps distinguish the mechanisms characteristic of each phenomenon or element, fostering a more structured and accurate understanding of the processes involved. In this case, it enables comprehension of the natural greenhouse effect as a physical process of infrared radiative energy balance, while the ozone layer acts as a UV filter, without intervening in this balance (Harrison & Treagust, 2006). In this way, analogies serve as cognitive anchors that help students establish clear conceptual boundaries, supporting the construction of mental models and a more precise interpretation of atmospheric processes (Eriksson et al., 2024).

Conclusions

This study analysed participants' conceptions of the greenhouse effect, identifying alternative conceptions that persist across different educational stages, even among students at higher levels. The results reveal difficulties, particularly in differentiating between the greenhouse effect and concepts such as the ozone layer and climate change. Although the university-level participants in this study demonstrated a greater ability to integrate technical aspects, such as the reflection and absorption of solar radiation, other alternative conceptions persist, such as viewing the ozone layer as part of the greenhouse effect, which hinders the achievement of the reference school-science model.

These findings highlight the need to implement educational strategies that address these difficulties from early stages, designing teaching–learning proposals that promote a clear and precise differentiation of these concepts (Andersson & Wallin, 2000). Model-based teaching strategies and the use of modelling resources may be effective approaches to this end (Papadimitriou, 2004). In this regard, the use of carefully selected analogies, guided by the teacher, is understood as a viable option to facilitate the understanding of the physical processes involved (Harrison & Treagust, 2006; Eriksson et al., 2024).

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Assessing Climate-Change Competence in Pre-Service Teachers: Knowledge, Attitudes, and Behavioural Engagement in Climate Education

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The effects of accelerated climate change on nature and society are evident, primarily driven by human-induced greenhouse gas emissions, causing severe and often irreversible damage. Despite scientific consensus, climate change denial has increased, particularly among far-right political groups, hindering mitigation efforts and heightening societal uncertainty. Education plays a crucial role in addressing this challenge by fostering climate literacy, equipping individuals with knowledge, skills, and attitudes necessary for action. The Climate-change Competence (C3) framework was introduced to assess climate literacy in education, later refined to evaluate pre-service teachers in different countries, emphasizing its role in shaping future societal responses. This study seeks to assess the level of climate-change competence among pre-service teachers at Universidad Complutense de Madrid, contextualizing the C3 framework within their specific educational environment. Our findings align with previous research, indicating that pre-service teachers in Madrid demonstrate high levels of climate- change competence, particularly in knowledge and attitude dimensions. They recognize the causes and consequences of climate change and express a proactive stance toward mitigation. However, their commitment to concrete actions remains moderate, especially in areas related to food and diet. No significant differences were found based on academic background or gender, except in attitudes, where undergraduate and female students showed greater commitment. These results reinforce the need to strengthen behavioural engagement strategies in climate education to enhance real-world action

Keywords: Climate Change Competence, Pre-Service Teachers, Spain

Introduction

Context And Theoretical Framework

The impacts of accelerated climate change on natural systems and human societies are indisputable (Wheeler and Von Braun, 2013; Dao et al., 2023; Abbass et al., 2022). In its most recent report published in 2023, the Intergovernmental Panel on Climate Change (IPCC) has reaffirmed the anthropogenic origin of global warming, primarily driven by greenhouse gas emissions, which is leading to significant, and in some cases irreversible, damages and losses. However, despite the scientific consensus confirming accelerated climate change as a factual phenomenon, climate change denial has intensified in recent years (Washington and Cook, 2011; Dunlap & Brulle, 2020). In this context, far-right parties and political actors are increasingly promoting denialist narratives regarding the consequences of climate change (Gruber, 2025), hindering the adoption of mitigation measures, complicating efforts to alleviate current impacts, and increasing societal uncertainty (Wong-Parodi and Feygina, 2019).

Nevertheless, governments have access to a broad range of policies and strategies to address climate change. Among the various actions aimed at mitigating its effects, education emerges as a central element for enhancing knowledge, skills, and attitudes in response to the social and environmental challenges posed by climate change. Numerous studies highlight the importance of climate change literacy as a key tool to confront this issue effectively (Johnston & Cook, 2019; Nusche et al., 2024). Given their pivotal role within educational systems, teachers constitute one

of the fundamental pillars for fostering climate change literacy among students, who are future citizens and among those most vulnerable to climate change impacts. However, there is currently no clearly defined approach or legislative framework to systematically guide the implementation of this educational responsibility across different states.

To begin developing a strategy that positions education as a driving force for societal mobilisation, it is essential to assess the extent to which current educational systems prepare students to understand climate change, raise awareness, and promote action (Fuertes et al., 2020). In their seminal work, Fuertes et al. (2020) introduced the concept of Climate Change Competence (C3), defined as a "framework to develop understanding, awareness and abilities related to Climate Change through Education", enabling individuals to effectively address the global crisis through formal education. Subsequently, Ferrari et al. (2022) operationalised this competence by defining three distinct dimensions through a validated assessment questionnaire comprising 36 items, administered to a sample of over 500 primary and secondary school teachers. More recently, these dimensions were revised and adapted for pre-service teachers in Honduras and Spain using an updated set of items (Ferrari et al., 2024).

Aims Of The Research And Hypothesis

This study aims to determine the degree of climate-change competence of the pre-service teachers from the Universidad Complutense de Madrid (Madrid, Spain), defining the C3 competence in their context.

In the Spanish context, pre-service teachers are trained within higher education programs that increasingly acknowledge sustainability and climate change, yet research consistently shows important gaps between curricular intentions and actual competences. Previous studies indicate that Spanish pre-service teachers tend to display limited and fragmented environmental and climate-related knowledge, while simultaneously expressing generally positive attitudes, a sense of responsibility, and a moderate level of pro-environmental behaviour (Álvarez García et al 2018). This imbalance suggests that favourable dispositions towards environmental issues are not always accompanied by sufficiently robust conceptual understanding or by a strong capacity to translate concern into effective educational practice. Moreover, recent evidence highlights the central role of affective dimensions in this context (Ballegeer et al, 2024; Fuertes-Preito, et al, 2024). Subject-matter knowledge alone does not directly predict pre-service teachers' willingness to engage in climate change education, but rather exerts an indirect influence mediated by attitudes and emotional engagement. Emotions related to climate change appear to act as key activating or inhibiting factors, shaping both mitigation-oriented behaviours and the intention to include climate change in future teaching. In fact, Spanish pre-service teachers can be broadly characterized into distinct profiles, ranging from more "concerned" individuals, who show higher levels of climate-change competence and a stronger willingness to act as educational change agents, to more "sceptical" ones, who exhibit lower competence and reduced engagement. Taken together, this body of research suggests that the specific context of Spanish pre-service teachers is defined by a combination of insufficient knowledge, generally positive but unevenly operationalized attitudes, and emotionally driven dispositions that critically condition their readiness to teach about climate change.

Table 1. Resume of the subdimensions conforming the dimensions of the C3 competence, including the mean values for each subdimensions and dimensions of the students included in the analyses. D: dimensions; n: number of variables included in the analyses; T: Whole dataset; Dg: Degree; Ms: Master; M: Male; F: Female.

D	Sub-D	n	Definition	Mean Sub-Dimensions					Mean Dimensions		
				T	Dg	Ms	M	F	T	Dg Ms	M F
KNOWLEDGE	BPP	3	Biophysical Processes	4,10	4,10	4,08	4,20	4,08	4,12	4,10 4,16	4,18 4,10
	CAU	6	Causes	4,15	4,14	4,20	4,25	4,13			
	CQS	4	Consequences	4,47	4,48	4,45	4,43	4,48			
	MIT	5	Mitigation	3,80	3,77	3,92	3,90	3,78			
ACTION	MAC	2	Consumption	3,44	3,45	3,38	3,44	3,44	3,32	3,32 3,35	3,37 3,31
	TRA	2	Transportation	3,55	3,54	3,60	3,70	3,53			
	ESA	2	Energy saving	3,55	3,97	4,14	4,08	3,99			
	F&D	2	Food and Diet	2,31	2,31	2,29	2,27	2,31			
ATTITUDE	CON	5	Concern	4,40	4,42	4,31	4,22	4,43	4,07	4,09 3,98	3,94 4,09
	LOC	5	Personal efficacy to act	3,82	3,88	3,55	3,54	3,87			
	HOP	4	Hope	3,73	3,76	3,61	3,63	3,75			
	WTT	3	Willingness to teach	3,90	3,86	4,06	3,96	3,88			
	EDR	5	Actions on Schools	4,37	4,38	4,30	4,24	4,39			
	POL	5	National Policy support	4,06	4,08	4,01	3,99	4,07			

Research Methodology Design And Materials.

Following the methodology described by Ferrari et al (2022), and considering the adaptations proposed by Ferrari et al (2024) where the main dimensions and subdimensions of the Climate-Change Competence (C3) were redefined (table 1), the climatic competence of preservice teachers from the Comunidad de Madrid (Spain) was determined. By means of a closed-ended Likert-scale test formed by 53 questions (Ferrari et al., 2024), with five response categories (from false/never/totally disagreed to true/always/totally agreed), the C3 competence spectra was defined for a total of 316 students from six different degrees, all pertaining to the Facultad de Educación – CFP (Universidad Complutense de Madrid). The mean values of the whole set of questions defining the subdimensions of the climate competence spectra were calculated, together with the means for the dimensions.

In order to determine if gender or university background condition the C3 competence spectra, U-Mann Whitney (non-parametrical) and T-Student (parametrical) analyses on C3 competence dimensions were performed (depending on the distribution of the data groups).

Results

Tables 1 (previous page) and 2 resume the results for these analyses defining C3 competence spectra of preservice teachers from the Universidad Complutense de Madrid and its relationship with gender and university background.

Table 2. Results of the statistical analysis to compare C3 competence dimensions between students from different university backgrounds and between genders.

		n	KNOWLEDGE		ACTION		ATTITUDE	
			Mean	Statistics	Mean	Statistics	Mean	Statistics
University background	**Degree**	259	4,11	p = 0.289 U = 1.059	3,32	p = 0.590 U = 0.590	4,09	**p = 0,048** **T = 1.681**
	Master	57	4,16		3,35		3,98	
Gender	**Male**	44	4,18	p = 0.096 U = -1.667	3,38	p = 0.403 U = -0.837	3,94	p = 0.055 T = -1.629
	Female	271	4,10		3,32		4,09	

Discussion

Our results are aligned with those exposed by Ferrari et al (2022) and (2024), with relatively high values for all three dimensions of the Climate-change competence. Pre-service teachers from Madrid demonstrate an adequate capacity to identify the principal causes and consequences of climate change (mean scores for knowledge dimensions and subdimensions close to 4, reflecting agreement with the test items and statements), and they also display a proactive stance towards addressing climate change (mean values for attitude dimensions and subdimensions near 4, indicating agreement with the proposed actions included in the questionnaire). However, in line with previous research on climate change mitigation behaviours among both pre-service and in-service teachers (Seroussi et al., 2019; Banos-Gonzalez et al., 2021; Tolppanen et al., 2021), our results reveal a moderate level of commitment regarding the actions undertaken to reduce the

causes and impacts of climate change (mean values for action dimensions and subdimensions around 3.5, suggesting partial engagement in climate action), with behaviours related to food choices and dietary habits obtaining the lowest scores. Conversely, no significant differences were observed in C3 competence according to university background or gender, apart from the attitude dimension, in which undergraduate students showed a higher level of commitment to combating climate change than postgraduate students

These patterns are evident not only when analysing the full sample, but also when considering university background and gender, with consistently higher scores in the knowledge and action subdimensions. No statistically significant differences were found (results not shown) across most subdimensions between undergraduate and postgraduate students, nor between males and females, except for LOC and WTT, which did show significant differences. However, minor variations can be identified in the attitudinal subdimensions. Overall, these findings are consistent with previous research on climate change awareness influenced by academic background and gender (Clayton et al., 2023). In general, undergraduate students obtained higher scores than master's students, reflecting a more proactive attitude towards addressing the causes of climate change. A plausible explanation for this pattern is that the more advanced and specialized training of master's students may be associated with a higher level of critical awareness, scepticism, and a deeper understanding of the structural limitations, uncertainties, and shortcomings of many climate change mitigation actions implemented in practice. This greater recognition of complexity may, in turn, reduce their perceived efficacy and willingness to adopt a proactive stance. The same difference can be observed for male and female students, where women are more willing to take action to preserve the environment.

Conclusions

Our findings shown that pre-service teachers from Madrid exhibit relatively high levels of Climate-change competence, particularly in knowledge and attitude dimensions. They recognize the causes and consequences of climate change and express a proactive stance toward mitigation. However, as observed in previous studies, their actual commitment to climate action is moderate, with lower engagement in behaviours related to food and diet.

No significant differences were found in Climate-change competence across academic backgrounds or gender, except in the attitude dimension, where undergraduate students displayed greater commitment than postgraduates. Similarly, female students showed a higher willingness to act than males, consistent with prior studies. These results reinforce the importance of integrating behavioural engagement strategies in climate education.

Following the exploration of Climate-change Competence (C3) among pre-service teachers (PSTs) at the Facultad de Educación – CFP of the Universidad Complutense de Madrid (UCM), future research aims to further investigate this competence in relation to didactic variables that reflect PSTs' concerns regarding Climate Change Education. This study will extend beyond the Comunidad de Madrid, incorporating samples from other Spanish regions as well as countries such as Honduras.

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Students' Misconceptions About Heatwaves And Their Interconnection With Climate Change

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The increasing frequency and severity of heatwaves globally highlights the urgency of integrating this pressing issue into education. Providing future generations with the knowledge to comprehend the science behind heatwaves and their relationship to climate change is essential. Such knowledge empowers students to adapt effectively, develop resilience, and acquire skills necessary for a sustainable future. This study assesses school students' perceptions and knowledge of heatwaves among secondary students from Belgium, Greece, Italy and Romania. A quantitative approach was employed, with data gathered through a questionnaire (N=392). The findings reveal that while some students have basic understanding of heatwaves, significant misconceptions persist, particularly concerning the connection between heatwaves and climate change. Furthermore, many students cannot directly decide the relation between heatwaves and health risks. These results underscore the need for targeted educational interventions. By enhancing students' understanding of the causes and effects of heatwaves, educators can foster a more engaging and impactful learning experience. These efforts are crucial for enhancing preparedness and creating a generation better equipped to tackle climate change challenges.

Keywords: Environment, Science Education, Sustainability

Introduction

Heatwaves pose a growing natural hazard with severe consequences for human health, ecosystems and infrastructure (Murray et al., 2012). Despite the scientific consensus on the interconnectedness of climate change, global warming, and heatwaves, pervasive misconceptions continue to endure (Bostrom et al., 1994). These misconceptions encompass a lack of clarity regarding the relationship between heatwaves and climate change confusion surrounding the mechanisms that cause heatwaves (Williams et al., 2019), underestimation of the health hazards posed by heatwaves, and a widespread deficiency in knowledge about proactive measures for heatwave preparedness (Lampl et al., 2023). These arise from complex factors, hindering public understanding and response such as, (a) limited scientific literacy (Chowdhury et al., 2012), (b) representations in the media (Perkins, 2015), (c) personal experience bias (Ruth et al., 2019), (d) information overload and fatigue (Perkins, 2015), (e) lack of trust in authorities (Chowdhury et al., 2012).

The need for targeted public education campaigns that emphasize the dangers of heatwaves and provide clear guidance on risk abatement and preparedness strategies is evident (Yepéz et al., 2019). By incorporating the issue of heatwaves into school curricula, we foster climate literacy to make informed decisions and advocate for effective mitigation and adaptation strategies (VanderMolen et al., 2022). Understanding students' existing perceptions of heatwaves, including their potential misconceptions, is important for designing targeted educational interventions that foster scientific knowledge and promote responsible environmental stewardship (VanderMolen et al., 2022). Based on the above, we considered it valuable to investigate whether school students are aware of the widespread presence of heatwaves and their associated health risks. The research questions guiding our study are:

(R.Q.1) How do students self-report their level of environmental awareness ?

(R.Q.2) How well are students informed about (a) the prevalence of heatwaves and (b) the associated health risks, while interrelated with climate change, across the countries of the research?

(R.Q.3) What is the relationship between students' self-reported environmental awareness and experience of teaching with their perceived knowledge of heatwaves and their interconnection with climate change?

Materials And Methods

To address the above-mentioned questions, we conducted quantitative research involving N=392 students (grades 5–8) from Belgium, Greece, Italy and Romania. The participants were selected through convenience sampling, with their age and gender distribution shown in Table 1. Both ethical approval and license were obtained to conduct the research.

Table 1. Age and gender of the sample per country and in total.

		Country				
		Belgium N=62	**Greece N=120**	**Italy N=70**	**Romania N=140**	**Total N=392**
Age	mean±SD	13.77±0.15	12.55±0.07	12.81±0.167	15.62±0.14	13.69±0.13
Gender	Male N(%)	30(48.4)	59(49.2)	39(55.7)	84(60.0)	212(54.1)
	Female N(%)	32(51.6)	58(48.3)	31(44.3)	56(40.0)	177(45.2)
	Other N(%)	-	3(2.5)	-	-	3(0,7)

A 31-item questionnaire was developed and distributed online to students via Google Forms during the November of 2023, to evaluate their knowledge of heatwaves, including their prevalence and associated health risks. The questionnaire has been based on insights from relevant literature (Arslan et al., 2012; Cheng et al., 2019; Fernandez et al., 2015; Huang et al., 2011; Macintyre et al., 2018; Koutra-Heliopoulou et al., 2023; Meehl & Tebaldi, 2004). Besides questions about the profile of the sample (6 items addressing age, country, grade, gender, environmental awareness, and students' teaching experiences), 25 5-point Likert scale items (1=totally disagree to 5=totally agree) focused on:

(a) *General Knowledge* about heatwaves (GK) (C1-C16) including heatwaves' prevalence, and their interconnections with climate change,

(b) *Health Knowledge* (HK) about Heatwaves and their associated health-risks (C17-C25). Negatively worded items were reversed so that scores ranged from 1 (low knowledge) to 5 (high knowledge).

It is important to clarify that the item on students' teaching experiences referred to any formal lessons, workshops, or classroom discussions students had received about heatwaves, climate change, or related environmental topics.

The reliability of the instrument and the two subscales was estimated based on Cronbach's alpha and the results were considered moderate and acceptable (Nunnally, 1978; Taber, 2018) (Table 2).

Table 2. The questionnaire's and subscale's reliability.

Subscale	Cronbach's Alpha	Items
General_ Knowledge about heatwaves	.695	8
Health_ Knowledge about heatwaves	.612	17
Total	*.740*	*25*

Results

Students self-reported a medium level of environmental awareness (3.48±0.87), and a low level of exposure in heatwaves teaching (1.58±0.49), which varied significantly across the countries (F=15.646, p<.001). Students from Italy have received the most extensive teaching about heatwaves (=1.91±0.28) compared to the others.

They demonstrate a medium level of knowledge about heatwaves and their health-related issues (Health Knowledge – HK), as well as their prevalence and connections to climate change (General Knowledge – GK), However, scores differ significantly between countries (Table 3), with students from Greece and Romania showing the highest levels.

Table 3. Students' knowledge about heatwaves.

	Belgium	Greece	Italy	Romania	Total
Health _ Knowledge*	3.26±0.306	3.63±0.695	3.34±0.438	3.61±0.712	*3.52±0.635*
General _ Knowledge**	3.00±0.304	3.48±0.459	3.08±0.343	3.40±0.420	*3.30±0.444*

*F=7.209, p<.001, **F=25.65, p<.001.

Going deeper on students' answers (Table 4) regarding their General Knowledge of heatwaves, our findings show that 53.9% of students recognize the link between climate change and heatwaves (Q5) and 56.4% of students recognize that climate change makes heatwaves more frequent and intense (Q3), whereas only 22.2% are aware of the broader economic impacts of heatwaves on European cities, such as reduced productivity and tourism (Q10).

Regarding students' Health Knowledge of heatwaves (Table 4), the data reveal significant gaps. Only 49.5% of students correctly associate extreme heat with heat-related illnesses (Q22). Furthermore, 46.9% identify excessive sweating as a sign of heat stress (Q23) and only 55.8% of students recognize that individuals with heart problems are more vulnerable during heatwaves (Q24). However, 49.6% understand that the elderly and young children are more susceptible (Q25), showing that nearly one-fifth may not fully grasp the disproportionate risks for these groups.

Table 4. Students' distribution of answers in each item regarding their knowledge about heatwaves.

Questions	Disagree*	Neutral	Agree
General Knowledge			
Climate change is making heatwaves less frequent and less intense.	32.6%	32.4%	34.9%
Climate change is making heatwaves more frequent but less intense.	36.4%	36.5%	26.5%
Climate change is making heatwaves more frequent and more intense.	17.6%	26.0%	56.4%
Climate change is making heatwaves less frequent but more intense.	34.3%	36.1%	29.6%
Climate change has no connection to heatwaves.	53.9%	24.6%	21.5%
Heatwaves do not affect European cities differently from other regions.	35.1%	35.3%	29.6%
Heatwaves can lead to an increase in air pollution in European cities.	15.8%	29.9%	54.2%
Heatwaves can cause an increase in energy demand and strain on the power grid in European cities.	16.1%	36.8%	47.0%
Heatwaves can cause negative health impacts for vulnerable populations in European cities.	14.6%	31.2%	54.2%
Heatwaves can lead to economic impacts such as decreased productivity and tourism in European cities.	18.6%	34.5%	49.9%
Heatwaves can exacerbate the urban heat island effect in European cities.	17.7%	42.4%	39.9%
Heatwaves affect cities the same way across Europe.	33.2%	31.6%	35.2%
Sprinklers in open grounds and fans can play a role in cooling.	20.7%	41.6%	37.8%
Creating forests within cities and green corridors are an effective way to shift airmass to cool large areas within a city.	17.3%	32.3%	50.4%
If you wear dark clothes you feel cool in summer.	55.4%	23.3%	21.3%
Windows and doors should be opened at noon on hot days.	36.8%	28.9%	34.2%
Health Knowledge			
Fever, fatigue, and chest tightness are common symptoms of heat stroke.	16.3%	35.5%	48.2%
Some medicines can increase the risk of heatstroke.	23.8%	38.6%	37.6%
High environmental temperature can cause death.	14.6%	31.9%	53.5%
Heat waves are caused by high temperature and low rainfall.	15.8%	29.4%	54.8%
Extreme heat exposure is responsible for heat-related illnesses.	16.8%	33.7%	49.5%
Excess sweating during a heat wave can be a sign of heat stress.	14.9%	38.1%	46.9%
Individuals suffering from heart problems are highly vulnerable during a heatwave.	13.6%	30.6%	55.8%
The elderly and young ones are more vulnerable during a heat wave.	18.1%	32.3%	49.6%
The greenhouse effect is mainly caused by the depletion of the ozone layer.	17.6%	40.1%	42.3%

Students' environmental awareness and teaching experience show a very low but statistically significant correlation with HK and GK (r= .147, r=.005) (r= .134, r=.011).

Discussion

Our results highlight gaps in heatwave education despite students reporting a moderate level of environmental awareness. The findings reveal notable differences in students' environmental awareness across countries, reflecting disparities in the prioritization of heatwave education. These variations may stem from differences in national curricula, the perceived local relevance of heatwaves, or broader environmental education policies, issues that merit further exploration. Greece and Romania demonstrated higher, though still moderate, levels of knowledge, suggesting either a stronger educational emphasis or more extensive public awareness initiatives. However, additional research is needed to substantiate these interpretations. Targeted educational interventions may be particularly beneficial for Belgium and Italy, where students' understanding appears more limited.

Students' knowledge about heatwaves also varied substantially. Many were unaware of the broader economic consequences of heatwaves on European cities, indicating a need for more comprehensive climate education that addresses both direct and indirect impacts. Only about half of the participants correctly associated extreme heat with heat-related illnesses or recognized excessive sweating as a symptom of heat stress, findings that reinforce earlier calls (Knowlton et al., 2009) for more systematic education on the health dimensions of heat exposure. As Hajat et al. (2014) emphasized, the lack of recognition of heat stress symptoms can delay appropriate responses, thereby increasing health risks.

Furthermore, nearly one-fifth of students did not fully grasp the disproportionate risks that heatwaves pose for vulnerable populations such as the elderly, young children, and individuals with pre-existing health conditions. The weak correlation between students' environmental awareness, teaching experiences, and their knowledge of heatwaves underscores the need for targeted educational strategies that explicitly link these domains.

Overall, although many students recognize the connection between climate change and heatwaves, significant gaps in understanding remain. Addressing these through focused climate and health education could strengthen students' preparedness, enhance adaptive behaviours, and build resilience to climate-related challenges.

Taken together, future directions in climate change and heatwave education should move beyond the mere transmission of scientific facts toward cultivating students' sense of agency and connection to global environmental challenges. Educational interventions must be intentionally designed to embed these topics within science curricula in ways that are both contextually meaningful and socially relevant. Such approaches should aim to challenge misconceptions, deepen conceptual understanding, and foster adaptive and responsible action. Cross-national research will be essential to continue to explore how diverse educational contexts can sustain these transformative learning experiences, ensuring that education in climate change and sustainability becomes an empowering dimension of students' scientific literacy and civic identity.

Limitations

The small sample size per country limits the generalization of our conclusions to the broader population in the countries researched. At the same time, relying on self-reported measures introduces potential biases like social desirability and recall errors. Additionally, while demographic factors were considered, other relevant variables were not included.

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First Approaching To Preservice And Inservice Teachers Conceptions About Groundwater

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Meeting the enormous water needs of the human population and the agricultural, industrial and technological sectors is a sustainability challenge recognised by the United Nations. The overexploitation and pollution of aquifers pose a major threat to freshwater availability, especially in a context of climate change and increasing demand. This situation, in addition to being an environmental challenge, represents an educational one: understanding how groundwater systems function is essential for preparing citizens to make informed decisions about water management. This study explores the knowledge of primary and secondary school teachers (78 trainee and practising teachers) about groundwater and aquifers through an exploratory design with quantitative and qualitative analyses. The results show limited knowledge of the concept of aquifers and groundwater, as well as of their distribution and movement. Therefore, there is a need to reinforce and improve teachers' understanding of this topic, given its importance for humanity and ecosystems.

Keywords: Science Literacy, Teacher Beliefs, Groundwater

Introduction

The demand for water has increased exponentially over the last century (Boretti and Rosa, 2019), leading to the overexploitation of aquifers (Andreu Rodes and Fernández Mejuto, 2019), as well as the effects of climate change (Abtew and Melesse, 2013) and pollution (Andreu Rodes and Fernández Mejuto, 2019). Ensuring the availability of water for humanity and ecosystems is therefore considered essential for sustainability and is explicitly reflected in the SDGs. However, several studies have shown that groundwater—the largest reservoir of liquid freshwater on Earth—barely appears in students' representations of the water cycle (Ben-Zvi-Assarf and Orion, 2005a; Pan and Liu, 2018), or appears exclusively as lakes, rivers or underground caves (Ben-Zvi-Assarf and Orion, 2005a; Ben-Zvi-Assarf and Orion, 2005b; Covitt et al., 2009; Unterbruner et al., 2016). Textbooks also show room for improvement in this respect (Reyero et al., 2007; De Pedro Rodríguez & de Soto García, 2023), contributing to the persistence of alternative conceptions.

Teachers play a key role in educating a citizenry that is aware of and responsible for these challenges. However, research on teachers' conceptions of groundwater is scarce, despite its relevance for scientific literacy and sustainability education. This preliminary work therefore seeks to answer the following questions: Do teachers know the quantitative importance of groundwater within total continental liquid water? Do they have an adequate understanding of what an aquifer is and how groundwater behaves?

Methodology

The research has an exploratory scope. Data collection combines quantitative and qualitative approaches through a questionnaire containing open and closed questions. It was administered anonymously at the beginning of several groundwater workshops, meaning that sampling was

non-random and based on convenience. Table 1 shows the questions linked to the research questions posed.

Table 1. Survey questions regarding groundwater.

It marks the percentage represented by groundwater among continental liquid waters <5; 5-20; 20-40; 40-60; 60-90; >90%
What is an aquifer?
Draw how the water is found in the subsoil, take a photograph and upload your drawing here.
How does groundwater move?

A total of 78 individuals participated in the study, providing informed consent: 32 pre-service primary school teachers (PSTP), 31 pre-service secondary school teachers (PSTS) (graduates in Biology, Environmental Sciences, Geology, Geological Engineering and Biochemistry, in decreasing proportion), and 15 in-service teachers (IST), including 8 graduates in Education or other non-scientific fields and 7 with scientific degrees.

Quantitative data analysis focuses on describing the results obtained. Qualitative analysis was conducted using a category system defined inductively through an in-depth reading by the authors (Table 2). The reliability of this system was verified through an inter-observer process in which two researchers applied the category system to a 20% sample of the responses. The resulting coding was subjected to a concordance analysis (Cohen's kappa) using Epidat software. The value obtained (0.849) indicates a high level of agreement (Landis and Koch, 1997). The few discrepancies were resolved among the authors, and the final application of the system was carried out on the full set of qualitative data.

Table 2. Inductively generated system of categories and subcategories.

Category	Subcategory (code)	Description
Definition/representation of aquifers and groundwater	Material capable of holding water	Rock formation or geological material with pores or holes in which water can be stored by infiltration.
	Lake/Pond/River/Place where the water is found in the subsoil	Cavity, stream, or area where groundwater is located
	Reservation/Deposit/Warehouse	Water storage susceptible to exploitation by man
	It is connected to the outside (rivers, sea, sea, etc.).	The water in the subsoil is not stagnant, but communicates with rainwater and/or water from rivers/lakes
Groundwater behaviour	Infiltrates (without specifying where)	Penetrates down
	Moves between pores, capillaries	It penetrates, infiltrates through the gaps in the ground and rocks
	It moves by currents, roads	Similar to rivers or external streams
	Moves (others)	Other factors that condition movement such as gravity, water pressure, tides, etc.
	Unclear/ Don't know/doesn't answer	They do not answer or answers that are difficult to categorize.

Results

The first research question—whether teachers know the percentage of freshwater that groundwater represents within total available continental water—is addressed through the quantitative results of the first questionnaire item. Table 3 shows the results by participant group. Of the total sample, more than 30% believe that less than 20% of continental freshwater is stored underground (mainly among ISTs). Only 3 participants (4.2%) correctly identified the very high relative abundance of groundwater (>90%). Another 14 participants (17.9%) indicated that there is much more groundwater than surface water (PST). Among those who clearly recognised the subsurface as the main reservoir of available water, pre-service teachers stand out.

Table 3. Participants' estimates of groundwater abundance within total continental liquid freshwater.

SUBT WATERS	PSTP (n/%)	PSTS (n/%)	ACTUAL (n/%)	TOTAL (n/%)
<5%	0/0.0	3/9.7	3/20.0	6/7.7
5-20%	7/21.9	8/25.8	3/20.0	18/23.1
20-40%	7/21.9	3/9.7	3/20.0	13/16.7
40-60%	10/31.3	9/29.9	5/33.3	24/30.8
60-90%	6/18.8	7/22.6	1/6.7	14/17.9
>90%	2/6.3	1/3.2	0/0.0	3/3.8

The second research question—whether teachers have an adequate understanding of what an aquifer is and how groundwater behaves—is answered through the qualitative analysis. Regarding the definition of an aquifer, 47.4% associate it with an underground river, lake, stream or cavity, referring to it as "an underground lake". Another 20.5% (mainly PSTS and science-trained ISTs) define it correctly as a material or rock formation with pores that contain water, using expressions such as "a geological formation capable of storing water". A total of 28.2% (across all groups) describe it as a water reserve or reservoir, emphasising its usefulness for humans, e.g., "a water reserve underground". Only a minority (3.8%) mention infiltration from the surface. A single participant (PSTS) refers to the connection between aquifers and rivers from the inside out: "They recharge/discharge into areas such as rivers and lakes and through infiltration".

Regarding groundwater movement, no participant questioned whether groundwater moves. A total of 16.7% compare it to movements similar to those of rivers or surface streams ("through underground channels"). Another 17.9% describe circulation through pores or capillaries in the soil and rocks ("between the pores of the rocks"). Only 10.2% refer to flow velocity, using terms such as "slowly". A total of 24.3% mention factors that may influence movement, such as "pressure differences", "gravity", "capillarity", "following the slope from higher to lower areas", or "filtration". Finally, 3.8% refer to unrelated processes such as "tectonic movements" or "tides".

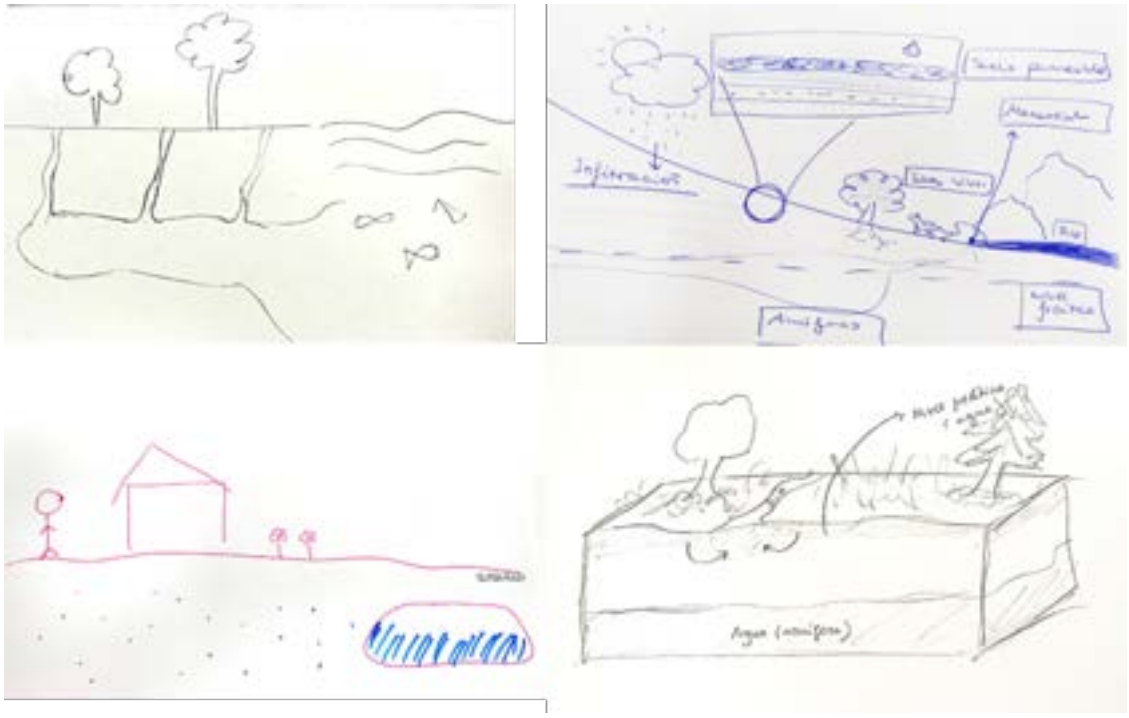
In the drawings, both the representation of groundwater and its connection with the surface and its movement were analysed. Most participants (73.1%) imagined groundwater as underground rivers or pockets (Figures 1a, 1c), sometimes as deep lakes, suggesting that they conceive of groundwater as the lower part of surface water bodies. A total of 21.8%, mainly science graduates, represented porous materials in some detail (sometimes with a magnifying glass), showing water between the pores (Figure 1b). Some drawings were clearly influenced by geology class diagrams, including elements such as the water table, arrows indicating water movement, and specific terminology.

A total of 62.5% of participants represented groundwater as connected to the surface, sea, rivers or springs (Figures 1a, 1b, 1d), while only 5.1% depicted connections from the subsurface to

rivers (winning streams, Figure 1d). Conversely, some drawings showed rivers, ponds or porous layers completely disconnected from the surface (Figure 1c). Only 7% included rainfall (only PSTS), despite it being the main source of groundwater recharge (Figure 1b).

Groundwater movement was represented by arrows or dashed lines in 30.7% of drawings, sometimes labelled as "infiltration" (Figures 1b, 1d). Only 3.8% appear to suggest movement through rock materials. In addition, 13.8% included human use of groundwater, depicting wells.

Figure 1. Drawings showing how participants imagine groundwater. 1a (top left), 1b (top right), 1c (bottom left), 1d (bottom right).



A minority of participants (less than 20%) are aware that groundwater accounts for a much larger volume than surface water. In addition, teachers' understanding of aquifer functioning is quite limited. This is worrying, as it aligns with findings in secondary school students (Ben-Zvi-Assarf & Orion, 2005a; Covitt et al., 2009; Pan & Liu, 2018). PSTS and IST science majors typically offer more precise definitions of aquifers, highlighting porous, permeable materials capable of harbouring water. Many participants consider groundwater an important reserve, which contrasts with their perception of its limited abundance.

The groundwater drawings analysed are excessively schematic, lacking representation of recharge (rain, rivers, lakes) and discharge into rivers or lakes, as well as indications of water movement (arrows). These results are consistent with previous studies (Ben-Zvi-Assarf & Orion, 2005a; Reyero et al., 2007; Pan & Liu, 2018). Recognising groundwater as the main contributor to surface freshwater is crucial, as aquifer overexploitation is aggravated by population growth and climate change.

Some drawings reflect common classroom images (underground layers, karstic aquifers), sometimes with inaccuracies. This highlights how representations influence participants' understanding (Reyero et al., 2007).

Our results urge a review of teacher training, given teachers' central role in citizenship education. Understanding groundwater is essential for addressing challenges such as overexploitation, pollution and the responsible management of this resource. The existing awareness of its importance is a valuable starting point for improving teacher education.

Key hydrogeological issues should be more present in curricula to advance sustainability. This study provides data on teachers' conceptions of groundwater. Despite being preliminary and based on a limited sample, it offers valuable insights into a population that is key to sustainability education.

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Pre-Service Teachers' Behaviours Toward Environmental Problems

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Environmental issues pose significant challenges to ecosystems, biodiversity, and human health, making it crucial to examine behaviours that contribute to sustainability. Teachers play a key role in shaping students' environmental attitudes and actions. However, there is limited research on how pre-service teachers engage with environmental problems in their daily lives. This study aims to investigate pre-service teachers' behaviours toward environmental problems across different grades and departments. A survey research design was employed, and data were collected from 829 pre-service teachers from science, mathematics, social sciences, and primary education departments at a university in Turkey. The Environmental Problems Behaviour Scale, consisting of six sub-dimensions (perception, formation, guidance, skill transformation, adaptation to the situation, and creation), was used as the data collection tool. Descriptive and inferential statistical analyses, including t-tests, ANOVA, correlation, and multiple regression analyses, were conducted using SPSS 26. The findings revealed that pre-service teachers scored positively on the environmental behaviour scale. No significant differences were found in total scores based on gender, grade level, or department. However, significant positive correlations were observed among all sub-dimensions of the scale. Regression analysis showed that gender and grade level significantly predicted environmental behaviours, though the explained variance was low.

Keywords: Environmental education, pre-service teacher education, quantitative research

Introduction

Environmental issues have become one of the most pressing global challenges, impacting ecosystems, biodiversity, and human health. These issues threaten not only the environment but also future generations, making it even more critical to address them. Addressing these challenges requires a fundamental shift in individual behaviours toward sustainability. Teachers, as role models in society, play a significant role in shaping environmental attitudes and behaviours among students (Clayton et al., 2021).

From a behavioural perspective, environmental sustainability is often discussed in the literature as extending beyond environmental awareness or knowledge and involving how individuals respond to environmental issues in their daily lives. Previous studies have suggested that environmental knowledge and concern do not always directly translate into pro-environmental behaviour, and this relationship has been examined from different theoretical perspectives (Kollmuss & Agyeman, 2002; Kaiser & Wilson, 2004). In this respect, focusing on behaviours toward environmental problems may provide a descriptive understanding of how sustainability-related orientations are reflected in everyday practices.

However, there is limited research on how pre-service teachers from different disciplines personally engage with environmental issues and adopt behaviours toward environmental problems in their daily lives (Kollmuss & Agyeman, 2002; Monroe et al., 2019). Most existing studies focus primarily on environmental awareness, attitudes, or knowledge levels, while empirical evidence on behavioural dimensions—particularly multi-dimensional behavioural constructs—is still scarce. This gap is especially critical in teacher education, as pre-service

teachers are expected not only to possess environmental knowledge but also to model sustainable behaviours for their future students. Teacher education programs are therefore strategic contexts for fostering environmentally responsible behaviours. Understanding whether such behaviours differ according to gender, grade level, or disciplinary background can inform curriculum design and policy decisions aimed at strengthening environmental education in higher education. Examining these differences may also reveal whether current teacher education programs provide equitable and effective opportunities for developing sustainable behaviours across different subgroups.

Therefore, this study aims to examine the behaviours toward environmental problems of pre-service teachers from various grades and departments. Specifically, the study seeks to determine (a) the general level of pre-service teachers' behaviours toward environmental problems, (b) whether these behaviours differ according to gender, grade level, and department, and (c) the extent to which these demographic variables predict environmental behaviour. Understanding these behaviours can help develop targeted strategies and educational policies to enhance environmental responsibility among pre-service teachers, ultimately contributing to a more sustainable future.

Method

Research Design

Survey research design was used to achieve the purposes of this study. In survey research, researchers are generally interested in how and to what extent responses vary -their variability- how closely some responses are related to others, and how responses differ based on specific demographic variables or measures of social, political, or psychological factors (Fraenkel & Wallen, 2009). In line with this approach, the present study aimed to describe pre-service teachers' behaviours toward environmental problems and to examine how these behaviours vary according to selected demographic variables.

Participants

Convenience sampling, a technique that selects settings, groups, or people who are easily accessible and willing to participate in research, was used to determine the participants (Onwuegbuzie & Collins, 2007). Due to their logistical advantages in terms of time and money, pre-service instructors who were enrolled at the university where one of the researchers was based were included in this context. 829 pre-service teachers (581 females, 248 males) from science (161), mathematics (277), social sciences (195), and primary education (196) departments of a university in the Central Anatolia Region of Turkey participated in the study.

Data Collection Tool

Data for this study were collected using the Environmental Problems Behaviour Scale developed by Güven and Aydoğdu (2012). The scale consists of 40 items designed to measure individuals' behaviours toward environmental issues. Items are rated on a 3-point Likert-type scale.

The scale is structured around six factors: Perception (four items), formation (eight items), guidance (six items), skill transformation (10 items), adaptation to the situation (five items), and creation (seven items). The total score obtained from the scale was used as an overall indicator of behaviours toward environmental problems.

Data Analysis

The data were analysed using descriptive and inferential statistics. In order to examine the relationships between participants' behaviours and demographic variables, inferential statistics,

including independent samples t-tests and one-way ANOVA, were applied. A correlation analysis was also performed to assess the relationships between the sub-dimensions of the environmental behaviour scale. Lastly, multiple regression analysis was conducted to identify the factors that significantly predict pre-service teachers' behaviours toward environmental issues. In the multiple regression analysis, the total environmental problems behaviour score was treated as the dependent variable, while gender, grade level, and department were included as independent variables. All data analyses were performed using SPSS 26.

Findings

The results indicated that the mean total score of all pre-service teachers on the 40-item 3-point Likert scale was 90.64 (*SD* = 9.94), suggesting a generally positive level of behaviours toward environmental problems among the participants. Mean total scores for the six dimensions were as follows: Perception (*M*=9.05, *SD*=1.81), formation (*M*=17.60, *SD*=2.58), guidance (*M*=13.33, *SD*=2.03), skill transformation (M=23.73, *SD*=3.25), adaptation to the situation (*M*=11.47, *SD*=1.78) and creation (*M*=15.45, *SD*=2.24).

According to the independent samples t-test results, no significant difference was found in the total scores between male (*M*=88.59, *SD*=9.93) and female pre-service teachers (*M*=91.51, *SD*=9.83), indicating that gender did not lead to a meaningful difference in overall environmental behaviour scores at the group comparison level.

Table 1. Intercorrelations among the sub-dimensions of Environmental Problems Behaviour Scale.

	Perception	Formation	Guidance	Skill Transformation	Adaptation	Creation
Perception	-					
Formation	,510**	-				
Guidance	,356**	,382**	-			
Skill Transformation	,556**	,570**	,395**	-		
Adaptation	,455**	,436**	,304**	,490**	-	
Creation	,413**	,345**	,296**	,385**	,379**	-

One-way ANOVA results revealed no significant difference in total scores between pre-service teachers from the 1st (*M*=90.12), 2nd (*M*=90.07), 3rd (*M*=90.40), and 4th years (*M*=91.99) (*F*=1.755, *p*>.05). Moreover, one-way ANOVA results revealed no significant difference in total scores between pre-service teachers from the science (*M*=91.40), mathematics (*M*=89.86), social sciences (*M*=91.44), and primary education (*M*=90.33) departments (*F*=1.367, *p*>.05).

According to the correlation analysis results between the sub-dimensions of the environmental problems behaviour scale, all of the six sub-dimensions showed significant positive correlations with other five sub-dimensions (Table 1).

A multiple regression analysis was conducted to investigate how well gender, grade, and department predict pre-service teachers' behaviours toward environmental problems. In this analysis, the total environmental problems behaviour score was used as the dependent variable.

Regression analysis revealed that gender and class year significantly predicted total scores. The first model, including only gender, explained 1.8% of the variance in total scores ($R^2 = 0.018$, $F = 15.244$, $p < 0.001$). When grade level was added to the model, the explained variance increased to 2.5% ($R^2 = 0.025$, $F = 10.727$, $p < 0.001$). Gender was a significant predictor ($B = 2.92$, $p < 0.001$), with males scoring higher than females, while grade level also showed a significant effect ($B = 0.752$, $p = 0.014$). Department was excluded as it did not contribute significantly. Collinearity diagnostics indicated no issues (VIF values near 1).

Discussion And Suggestions

The average score of 90.64 indicates generally positive behaviours toward environmental issues among pre-service teachers, which aligns with previous studies showing that educators are more likely to engage in environmentally responsible actions (Kollmuss & Agyeman, 2002; Monroe et al., 2019). Although previous studies have reported gender-based differences in environmental behaviours (Kollmuss & Agyeman, 2002), the present study did not reveal a statistically significant difference between male and female pre-service teachers when group comparisons were conducted. This finding suggests that, at the descriptive level, environmental behaviours are distributed similarly across genders within the sample. One possible explanation for this could be the increasing efforts in educational institutions to promote environmental awareness equally among all students, regardless of gender.

The findings indicate no significant differences in the total scores of pre-service teachers from different departments (science, mathematics, social sciences, and primary education) on environmental issues. This suggests that there is no discernible difference in the environmental behaviours of pre-service teachers across disciplines. Studies in the field of environmental education often show that individuals from various academic backgrounds do not exhibit significant differences in their environmental awareness and behaviours (Monroe et al., 2019; Erdogan, 2013). The similarity in environmental attitudes across departments emphasizes the importance of interdisciplinary approaches in environmental education programs. Such programs can be effective in enhancing environmental consciousness among all teacher candidates, as fostering sensitivity to environmental issues should not be limited to a specific discipline.

The significant correlations between the sub-dimensions suggest that the formation and perception of environmental issues play a central role in influencing other behaviours such as skill transformation, guidance, and adaptation to the situation. This aligns with the works of Clayton et al. (2021) and Monroe et al. (2019), who highlighted that teachers' environmental perceptions significantly shape their ability to guide students toward sustainable behaviours. Moreover, the study shows that pre-service teachers' perceptions and the formation of environmental knowledge are strongly interconnected, which reinforces the idea that effective environmental education programs should focus on both cognitive and affective components (Erdogan, 2013).

The regression analysis revealed that gender and class year significantly predicted pre-service teachers' behaviours toward environmental problems. Interestingly, although no significant difference was found in the t-test, females scored higher than males, which contrasts with typical

findings (Kollmuss & Agyeman, 2002). The effect of grade suggests that more experienced students may be more engaged in environmental behaviours, potentially due to cumulative exposure to environmental education throughout their academic journey (Monroe et al., 2019). Interestingly, the department variable did not significantly contribute to the model, supporting the idea that environmental awareness is shaped more by broader educational experiences than by specific disciplines (Erdogan, 2013). This suggests that an interdisciplinary approach to environmental education might be more effective than focusing on particular fields of study.

Based on the findings of this study, several suggestions can be made for future research. Future studies may benefit from incorporating additional psychological, contextual, or institutional variables to better explain variations in environmental behaviour. Longitudinal research designs could be employed to examine how behaviours toward environmental problems develop over time throughout teacher education programs.

In addition, qualitative or mixed-methods approaches may provide deeper insights into how pre-service teachers interpret and enact environmental responsibility in their daily lives. Expanding the research to include multiple institutions or different cultural contexts could also enhance the generalizability of the findings.

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Studying Students' Reasoning About The Ozone Layer Depletion In The Context Of Argumentation

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The study focuses on the reasoning of 64 Greek upper secondary school students articulated in the context of an argumentation process about the ozone layer depletion, as part of a teaching-learning sequence regarding electromagnetic radiation, atmospheric-related issues and relevant policies. Participants were provided with a scenario specially designed for this purpose, which included evidence that could be used to support claims for or against specific actions, through the elaboration of particular reasoning. Results show that argumentation processes based on appropriately designed scenarios for the factors affecting ozone layer depletion could help students, to a certain degree, in developing reasoning to support claims such as in support of the ban of CFCs. We have identified specific elements of students' reasoning and organized them according to complexity, variability and flexibility. We also identified evidence of students' reasoning fragmentation.

Keywords: Ozone layer depletion, Reasoning, Argumentation

Introduction

Several studies in recent science education research literature explore students' understanding of the electromagnetic radiation-related atmospheric issues, including the relevant mechanisms of interactions between electromagnetic radiation and substances (e.g., Howard et al., 2013; Papadimitriou, 2004). Many of these studies highlight student difficulties related to understanding of such mechanisms involving relevant types of electromagnetic radiation, including those connected with ozone layer depletion (e.g., Çokadar, 2013; Kaya, 2009; Nyarko & Petcovic, 2021; Papadimitriou, 2004). The corresponding students' mental models seem to be particularly interesting, not only because it is found that, across educational levels, they include many misconceptions (Çokadar, 2013; Leighton & Bisanz, 2003), but also, because those concerning the ozone layer formation appear to be incoherent (Howard et al., 2013). We note specifically the existing evidence supporting the fragmentation of knowledge about the ozone layer itself and the ozone hole in particular (Leighton & Bisanz, 2003).

This fragmentation and inconsistency in students' mental models, as well as the lack of understanding and their misconceptions, are expected to have an impact on their reasoning, when issues related to the ozone layer depletion are discussed in the context of an argumentation process. This is the main purpose that framed the design of this study.

Theoretical framework

Students' understanding of the concepts of ozone, ozone layer and ozone depletion has attracted major interest from science education researchers. The relevant literature provides us with findings at various educational levels, from kindergarten to undergraduate students and pre-

service teachers (Leighton & Bisanz, 2003; Nyarko & Petcovic, 2021; Kaya, 2009). Although often students of different ages and educational levels are aware of some characteristics of the ozone layer, such as its nature, location and/or composition (Boyes et al., 1995; Boyes et al., 1999; Kaya, 2009; Nyarko & Petcovic, 2021; Pekel & Özay, 2005), various difficulties are identified, such as those related to the type of radiation involved in ozone layer depletion and function (Çokadar, 2013) or the understanding of the mechanism through which, electromagnetic radiation causes the ozone depletion and/or formation and the function of ozone broadly or the ozone layer in the earth's atmosphere (e.g., Nyarko & Petcovic, 2021; Çokadar, 2013; Howard et al., 2013). In addition, students appear to have difficulty in identifying ozone at ground level (e.g., Çokadar, 2013; Dove 1996;) and in the upper atmosphere (e.g., Çokadar, 2013). In line with this finding, problems are also identified at different ages and grades due to students' confusion with respect to the role of ozone in the stratosphere and troposphere (Bodzin et al., 2014; Howard et al., 2013; Kılınç et al., 2008). For instance, college students commonly believe that ozone formation in both the stratosphere and troposphere is attributed to one and the same single mechanism and that possible scepticism concerning the ozone layer is attributed to the role of ozone as a greenhouse gas (Howard et al., 2013). Students' confusion between ozone layer or ozone layer depletion and acid rain is also documented, since for instance, ozone depletion is being associated with acid rain, with students considering that the ozone layer protects Earth from acid rain (e.g. Nyarko & Petcovic, 2021).

Students' misunderstandings are also reported in relation to difficulties in identifying specific substances causing the ozone depletion, since confusion appears with the greenhouse gases (Kaya, 2009; Nyarko & Petcovic, 2021; Papadimitriou, 2004). Relevant studies that have been conducted across various ages and grades, provide us with findings indicating confusion between greenhouse effect (or global warming) and ozone layer depletion, based on the idea that ozone layer depletion and/or ozone holes are often believed to cause the greenhouse effect (or global warming) due to the increased solar energy, radiation or heat reaching the Earth through those ozone holes (e.g., Boyes & Stanisstreet, 1997; Dove, 1996; Kılınç et al., 2008; Österlind, 2005; Papadimitriou, 2004; Rye et al., 1997), or specifically due to increased ultraviolet radiation reaching the Earth's surface through them (e.g., Boyes & Stanisstreet, 1997; Çokadar, 2013; Dove, 1996; Kaya, 2009; Nyarko & Petcovic, 2021; Österlind, 2005; Papadimitriou, 2004; Rye et al., 1997). This idea has been found to be often expressed in a variety of students' mental models with coherent characteristics (e.g., Niebert & Gropengießer, 2014). On the other hand, knowledge about the ozone layer and ozone hole seems to be fragmented for younger students, in the elementary grades, due to the use of partial models and the absence of complete ones (Leighton & Bisanz, 2003), while incoherent models for the ozone layer formation are also found to be expressed by college students (Howard et al., 2013).

Research Questions

The lack of students' understanding of the concepts of ozone, ozone layer and ozone depletion, as well as, their relevant misconceptions, are expected to have an impact on students' reasoning when issues related to the ozone layer depletion are discussed. Thus, in this study, 11th grade upper high school students' reasoning is investigated during the development of arguments concerning the ozone layer depletion in the context of a teaching-learning sequence on climate change. Our main research questions were:

1. To what extent can students exploit data available in a given scenario concerning the ozone layer depletion in order to develop reasoning supporting a particular claim?

2. What are the basic elements of the reasoning that students develop within an argumentation context for the support of a particular claim concerning whether students are for or against the ban of CFCs?

Methodology

Participants were 64 Greek upper secondary students of the 11th grade of public schools who voluntarily participated in the study during the academic year 2023-2024, after informed consent had been obtained from their parents/legal guardians. In the context of a wider teaching-learning sequence about argumentation, electromagnetic radiation-related atmospheric issues and relevant policies, participants attended (among others) one 1-hour lesson about the ozone layer and its depletion, which was designed on the basis of the 5E teaching model.

Thus, after the initial stage of 'Engagement', students were attended relevant to ozone layer formation and depletion videos and simulations, during the 'Exploration' and 'Explanation' stages. In those stages, the ways, in which ozone layer is formed and those, in which it could be depleted, were explored with references to the effect of both the UV radiation and the catalytic action of some agents like CFCs, while the relevant explanations included mechanisms at the molecular level and further analyses with references to also other affecting factors like solar radiation intensity. In the 'Elaboration' stage, further discussion took place for the causes and the consequences of the whole phenomenon. Finally, in the 'Evaluation' stage of this model (about 15 min duration), students were provided with a specially designed scenario, in which two opposing views are developed in the context of relevant argumentation concerning the banning of CFCs in relation to the ozone layer depletion.

According to this scenario, the Montreal Protocol has banned the use of certain substances (commonly called CFCs) in order to protect the ozone layer. Several years after the ban, the ozone layer has indeed recovered to a significant extent, but depending on the year, its concentration exhibits significant fluctuations. Thus, scepticism developed about whether the annual fluctuations in the intensity of solar radiation or the action of CFCs is the most decisive factor in the ozone layer depletion, what would have happened if CFCs had not been banned, and whether all this effort was worth it.

Students were asked to study the scenario and to develop reasoning in the context of an argumentation process, supporting one of the claims provided, i.e. whether they are for or against the ban of CFCs. In brief, claims can be articulated as follows:

C1: I do not support banning the use of CFCs

C2: I support banning the use of CFCs (according to the Montreal protocol)

Students' responses were qualitatively analysed according to a three-step scheme as follows:

1. Students' responses were categorized according to the claim (C1, C2...) they supported.
2. For each one of the claims, students' reasoning was analysed by two independent raters (two of the authors) to isolate every distinct reasoning element (R1, R2….) that had a specific meaning.
3. Based on the isolated reasoning elements, students' reasoning was articulated accordingly, and a relevant categorization was followed.

Results

Students' reasoning was analysed by two independent raters (two of the authors) and every reasoning element having a particular meaning was recorded. Following this procedure, 14

reasoning elements (R1-12) were isolated, where 6 of these have a frequency from 15 to 45. Table 1 presents these reasoning elements.

Table 1. Students' reasoning elements (frequencies per category).

	Reasoning elements	N
R1	UV radiation breaks down the ozone molecule (forming oxygen molecule and oxygen atom)	8
R2	CFCs break down the ozone molecule (forming oxygen molecule and oxygen atom)	18
R3	CFCs under UV radiation break down the ozone molecule (forming oxygen molecule and oxygen atom)	12
R3a	UV radiation breaks down CFCs molecules forming chlorine atoms	15
R3b	A chlorine atom reacts with an ozone molecule forming oxygen molecule and ClO (and Cl is regenerated)	15
R4	Depletion of the ozone layer happens	45
R5	Ozone layer protect us from the UV radiation	1
R6	Penetration of UV radiation (through the atmosphere) happens	4
R7	Banning CFCs does not help	2
R8	The use of CFCs has been forbidden	27
R9	CFCs are not necessarily useful for us	1
R10	Total destruction of the ozone layer is avoided	33
R11	Comparing rates of destruction and regeneration	4
R12	The ozone layer is affected by variations in solar radiation	8

Based on the above reasoning elements (R1-12), students' responses were categorized as shown in Tables 2 and 3, with the exception of four students who did not respond. Specifically:

Table 2. Categories of students' reasoning leading to C1 (Number of students).

Category	Reasoning	N
1	Due to R1, then R7, thus C1	1
2	Due to R1, then R4 and R7, thus C1	1
3	Vague	3

Discussion And Conclusions

As shown in Tables 2 and 3, only few students (N=5) support C1 (*I do not support banning the use of CFCs*) based on the role of the UV radiation and ignoring the role of CFCs in the destruction of the ozone molecules (2 students), supporting the aspect that, substances causing the ozone layer depletion are not always recognizable by the students (Kaya, 2009; Nyarko & Petcovic, 2021). The vast majority of the students (N=55) support C2 (*I support banning the use of CFCs*). A number of them (N=15) focus on the catalytic destruction of the ozone molecules

(R3a, R3b), without taking into account the contribution of the UV radiation, advocating those suggest students' difficulties in problems understanding of the relevant mechanism (Nyarko & Petcovic, 2021; Çokadar, 2013). However, many of those supporting C2 (a total of 27 students, R8) take into account this contribution to the CFCs action, whereas some of them (15 students) can describe the mechanism of such an action, reporting the two relevant stages (R3a and R3b).

Table 3. Categories of students' reasoning leading to C2 (Number of students).

Category	Reasoning	N
1	Due to R1 and R2 then R4, thus, in order to R10, C2	2
2	Due to R1 and R2 then R4 and R6, thus, in order to R10, C2	1
3	Due to R2 then R4, thus C2	2
4	Due to R2 then R4 and R6, thus C2	2
5	Due to R2 then R4, and due to R9, thus C2	1
6	Due to R2 then R4, thus, in order to R10, C2	1
7	Due to R2 then R4, thus, in order to R10, and although R12, C2	1
8	Due to R2 then R4, thus, in order to R5, C2	1
9	Due to R2 then R4, and due to R8 then R10, thus C2	3
10	Due to R2 then R4, and due to R8 then R10, although R1, thus C2	1
11	Due to R2, and due to R8 then R10, thus C2	2
12	Due to R2 then R6, although R1, thus C2	1
13	Due to R3 then R4, although R12, thus C2	2
14	Due to R3 then R4, and due to R8 then R10, thus C2	6
15	Due to R3 then R4, and due to R8 then R10, and R11, thus C2	4
16	Due to R3a and R3b then R4, thus C2	4
17	Due to R3a and R3b then R4, thus, in order to R10, C2	2
18	Due to R3a and R3b then R4, and due to R8 then R10, thus C2	3
19	Due to R3a and R3b then R4, thus, in order to R10, and although R1, C2	1
20	Due to R3a and R3b then R4, although R12, thus C2	1
21	Due to R3a and R3b then R4, and due to R8 then R10, although R12, thus C2	2
22	Due to R3a and R3b then R4, although R12, and R8 did not stop R4, thus C2	2
23	Due to R8 then R10, thus C2	4
24	Vague	6

Among the reasoning elements used by the students, R4 (Depletion of the ozone layer happens) is the most frequent, whereas it is quite common for the students to recognize that the use of CFCs has been forbidden (R8), a fact that led to R10 (Total destruction of the ozone layer is avoided). However, it is quite interesting to see that some combinations of reasoning elements appear more frequently than others. The combination of reasoning elements R3 then R4, as part of a larger set of reasoning elements, appeared 12 times. The reasoning category "Due to R3a and R3b then R4, thus C2" appeared 4 times on its own, whereas the same combination of reasoning elements, as part of a larger set of elements, appeared 11 times. Also, the reasoning category "Due to R2 then R4, thus C2" appeared 2 times on its own, whereas the same combination of reasoning elements, as part of a larger set of elements, appeared 13 times. In addition, the reasoning category "Due to R8 then R10, thus C2" appeared 4 times on its own, whereas the same combination of reasoning elements, as part of a larger set of elements, appeared 21 times. Thus, it is apparent that, although there is broad variation in the reasoning patterns displayed by the students in response to the ozone layer depletion scenario, there are some combinations of reasoning elements that appear more frequent, facilitating the articulation of the whole students' arguments. Some of these combinations, especially in cases of students supporting C2, lead to the development of quite sophisticated reasoning involving adequately relevant elements, whereas in other cases, the whole reasoning appears to be quite simple.

However, more interesting is to focus on the variability existing in students' reasoning, where various reasoning emerge across students from the combination of different reasoning elements. Based on this variability it could be quite safe to a certain degree, to conclude that the classroom discourse has not reached coherent group knowledge and the group's understanding displays signs of fragmentation. In addition to the variability of the distinct reasoning elements that were identified, the same reasoning element or the same combination of reasoning elements can be activated, organized and function as part of a larger set of various interconnected reasoning elements or/and combinations of them leading to the articulation of multiple reasoning patterns, indicating the flexibility of these reasoning elements (e.g., Zarkadis & Papageorgiou, 2020). In addition to the variability and flexibility of students' reasoning elements, the reasoning elements, especially those supporting C2, appear to vary in their level of complexity, with reasoning element R3 [CFCs under UV radiation break down the ozone molecule (forming oxygen molecule and oxygen atom)] being more complex compared to R2 [CFCs break down the ozone molecule (forming oxygen molecule and oxygen atom)] and R1 [UV radiation breaks down the ozone molecule (forming oxygen molecule and oxygen atom)], reflecting a varying level of complexity of their reasoning which can fluctuate depending on how many and which reasoning elements are activated and the way they are organized as well.

In addition, it is important to notice, that many of the students' reasoning elements have common characteristics with the rationale, the elaborations and explanations developed during the lesson implemented in the context of the present study. As a result, it seems that argumentation processes based on appropriately designed teaching interventions, including scenarios for the factors affecting ozone layer depletion, could help students, to a significant degree, in developing reasoning in order to support their claims, such as those supporting the ban of CFCs.

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Action Research On Climate Change Education In Lower Secondary School – Students' And Teachers' Experiences

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An action research study on the topic of climate change education was conducted in collaboration between science and social science education researchers and teachers at three lower secondary schools. After joint literature seminars, teachers planned and conducted teaching sequences on climate change, including an out-of-school visit to the collaborating university with a focus on increased local risk of flooding due to climate change. Interviews with students at the end of the study revealed that they appreciated the teaching sequence, tried to lead their personal lives in a climate-friendly way, but were not very engaged emotionally in climate change as an issue. Meeting notes and interviews with teachers show that science teachers prioritized teaching climate change as a physical phenomenon, but social science teachers expressed frustration with students' lack of emotional engagement and a perceived disconnect between students' knowledge of climate change and choices in their personal lives. Challenges in conducting action research in a situation with different objectives across the initiating municipality, and participating researchers, teachers, and students are discussed.

Keywords: Action research; Sustainability; Secondary Education

Introduction

Science education on the topic of climate change has primarily focused on students' development of knowledge of involved scientific phenomena, such as the greenhouse effect, and how they can contribute individually to mitigate climate change (Bofferding & Kloser, 2015). By limiting the focus to students' scientific knowledge and individual actions, there are many aspects of climate change that are not addressed in science teaching, including how society needs to adapt to climate change (Bofferding & Kloser, 2015; Kagawa & Selby, 2012), students' risk perception with regard to climate change (Aksit et al., 2018), and dealing with students' often negative emotions in relation to climate change (Ojala, 2016).

One important aspect of students' climate literacy is its influence on their willingness to act in climate-friendly ways (Garrecht et al., 2023). In this regard, climate-change education should aspire to develop of students' action competence, with the aim "to make present and future citizens capable of acting on a societal as well as a personal level" (Jensen & Schnack, 2006, p. 472).

Schools and teachers often lack tools for handling such complexities associated with climate change, and collaboration with educational researchers is an attractive option to develop relevant teaching approaches. In this light, the present study was initiated by the school administration of Karlstad, a medium-size municipality in Sweden, who contacted us as educational researchers regarding perceived anxiety in relation to climate change among secondary students in the municipality.

Aims And Research Questions

The overall aim of the study was to develop, conduct and analyse teaching sequences on the topic of climate change, with the ambition of supporting students' development of climate literacy (Garrecht et al., 2023). The study was guided by the following research questions:

- What didactical choices do teachers make and didactical challenges do they encounter in the context of teaching climate change?
- What are lower-secondary school students views on climate change, its impact on their everyday lives, and climate-change education?

Research Method And Design

A research project was formed with the purpose of developing, conducting, and analysing teaching sequences on the topic of climate change. The project team consisted of science and social science teachers from three lower-secondary schools in the municipality, and science education and social science education researchers.

The project team had a series of project meetings, that included literature seminars on the topic of climate psychology (Andersson et al., 2019), and sharing experiences of teaching climate change before and during the project. Our initial intention was to design the study as a participatory action research project (Eilks, 2018), where researchers and teachers collaborate in formulating research questions, designing teaching sequences, and analysing the enacted teaching. However, in reality, we came to take on more traditional roles, where researchers formulated research questions and analysed collected data, and teachers designed and carried out teaching sequences.

Teachers formed groups within the three schools and collaborated in planning the teaching of climate change (Nilsson, in press). In addition, students from the three schools (N = 150, age 14-15 years) visited the university for an out-of-school activity on climate change-related risk of flooding and local adaptations to such risk (Haglund et al., 2025).

Within the project, the following data have been collected:

- Meeting notes from the project meetings.
- Individual interviews and focus-group interviews with four (N = 4) of the participating social science teachers regarding their didactical choices and didactical challenges during planning and conducting climate change education (Nilsson, in press).
- Interviews with six (N = 6) of the participating students conducted after the teaching sequence on their experiences of the climate change education and their perception of climate change.
- Video data of pupils' engagement during the out-of-school activity (Haglund et al., 2025).

The present study focuses on the teachers' and students' experiences from the project. The student interviews have been analysed through thematic content analysis (Bryman, 2016).

Findings

Teachers' Views Of Climate Teaching

In the initial project meetings, some of the teachers, in particular science teachers, expressed that they did not recognise the description from the school administration that students have strong, negative emotions in relation to climate change. Instead, rather than being worried about increasing global temperatures, students were perceived to express concern about high petrol prices for their mopeds, in line with the focus of media and political debate in society during the time of data collection. In this light, these teachers prioritised teaching about the greenhouse effect as a physical phenomenon rather than addressing students' emotions with regard to climate change.

However, the interviews with the social science teachers revealed a more complex picture, identifying didactical challenges and dilemmas (Nilsson, in press). They expressed frustration that the students have a solid, factual knowledge of climate change, but do not manage to connect it to local risks or consequences for their everyday life. The students are concerned about getting high grades and cheap petrol, but not how to act in a climate-friendly way. Greta Thunberg, with her engagement in climate change, comes across as annoying to many students. With students' narrow focus on "will this be on the test?", the teachers struggled to bring global challenges into the classroom. In this regard, the teachers' personal values clashed with those of the students.

The teaching sequences that the social science teachers designed included watching the documentary film *2040* (Gameau, 2019), where students were introduced to examples of how current technologies and strategies might be used to mitigate climate change in the near future in order to stimulate a sense of hope. Students also compared the local risk of flooding and draught in locations close to rivers in Sweden and in Spain, and considered local adaptations and conflicts of interest in use of water (Nilsson, in press). In this way, the classroom teaching aligned with and built on the out-of-school visit to the university with a focus on flooding (Haglund et al., 2025).

Students' Views Of Climate Change And Climate Teaching

In the student interviews, the students expressed that they had enjoyed the climate change education, including the visit to the university. They appreciated the focus on concrete local risks of flooding during the visit to the university and getting to know how it has been addressed in urban planning:

> But it was also a bit, like… a wake up, or, what should I say… that we're in a risk zone in Karlstad, too… with flooding and things… /…/ to walk there and see places that you really know of and see that it can go bad. (Interview 1)

The students also appreciated the creative nature of the activities, such as how to respond to possible flooding scenarios, and the social setting during the out-of-school visit where they got to interact with students from other classes and representatives from the university student organisation Climate Students.

The students described that they try to act in a climate-friendly way in their families. In this regard, they showed an awareness of individual activities that are known to have a high impact on CO_2 emissions, such as flying on vacation, driving cars, and eating meat (Wynes & Nicholas, 2017), but also mentioned other activities that have less impact, such as reducing waste and recycling.

In line with the impression from the teachers, most of the students did not express strong, negative emotions with regard to climate change and how it is likely to affect their own future. However, after initial reassuring statements, more subtle worries were revealed. Three of the students said the following about their feelings in relation to climate change and its potential consequences in the future:

> Well, I sure don't have angst. /…/ I would say that if I have angst, it is angst about the animals. /…/ I mean, I care about the climate. And, of course, I think about the future, but… I am in the age where you focus on yourself, and mopeds… (laughter) (Interview 3)

> I don't get very anxious, but you can get a bit anxious about what will happen to future generations. Of course, if we don't stop… don't try to stop it now, there will be more and more problems for our children that will come. (Group interview, student 4)

> I don't want to live in a world that is horrible. And I don't want to give… to have my children live in a world that is horrible. You want to… but it is a bit tough to see that we will maybe live in a world where it is, like, crap to live. [laughter] (Interview 1)

In these interview excerpts, the students express concern about climate change, but do not see an immediate risk for themselves here and now, but rather for future generations or animals.

On the topic of how they may be affected by climate change, two of the students reflect on the consequences:

> And it is going to get a lot warmer, and we will maybe not have any snow in the winter, and things… so you will not be able to go skiing in Sweden, for example. (Interview 1)

> That we in Sweden maybe not will have access to as many different exotic fruits and stuff. There will not be enough to bring here, and that. It won't grow as well. (Group interview, student 5)

Not being able to ski or having a limited supply of exotic fruit come across as small and quite insignificant changes to their current way of living, which can be interpreted as naivety with regard to the likely impact on society of climate change.

Discussion

The study revealed large differences in perspectives on climate change among the teachers and researchers in the project team, the school administration that initiated the project, and the students that took part in the teaching. One reason for the different perspectives might be the rapid changes in the media focus, turning from sympathies with Greta Thunberg when the project was initiated to a concern about petrol prices when the teaching was planned. There may also be a difference in attitudes towards climate change depending on the place where the students lived and their schools were located, in a city or on the countryside.

However, there might be more fundamental reasons behind the differences between science teachers and social science teachers. The science teachers tended to prefer a focus on students' knowledge of climate change as a physical phenomenon, adhering to a traditional Vision I (Roberts, 2007) of scientific literacy. In contrast, the social science teachers had an ambition to address consequences for how the students lead their everyday lives and can engage in the community, which relates more closely to an alternative Vision II (Roberts, 2007) of scientific literacy.

The study highlights the need for a more integrated and interdisciplinary approach to teaching climate change in schools, one that bridges the differing perspectives among educators. While science teachers often prioritize a Vision I framework of scientific literacy, focusing on the physical phenomena that cause climate change, social science teachers emphasize the societal implications and students' roles as active citizens. These differing priorities reveal an opportunity for collaboration, where scientific understanding is combined with empowering students to develop the skills and confidence needed to make informed and responsible decisions in addressing climate change.

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Section: Transformative Learning In Environmental Education

ESERA 2025 Copenhagen

Fostering Environmental Science Competencies In The Anthropocene: Implementation Of The Four-Step AAAR Learning Cycle Using PISA 2025 Framework

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The Anthropocene highlights the growing impact of human activities on Earth's systems, creating complex environmental challenges that require more than scientific knowledge alone. This study investigated the effects of implementing the Four-Step AAAR (Awareness–Anticipation–Action–Reflection) learning cycle on upper secondary students' environmental science competencies, as defined in the PISA 2025 Science Framework. The study employed a mixed-methods, one-group pre-test–post-test design with 24 students in Northern Thailand, using community-based environmental issues, particularly plastic waste management, as the learning context. Quantitative data were collected through a PISA-aligned cognitive test and the Environmental Action Scale, while qualitative data were gathered from student reflections, classroom observations, and learning artifacts. The results showed a significant improvement in students' overall environmental science competencies, with large effect sizes across all competency dimensions. Qualitative findings indicated increased environmental awareness, stronger systems thinking, and the emergence of student agency through both everyday participation and leadership-oriented actions. The findings suggest that the AAAR learning cycle can effectively support competency-based and action-oriented environmental science education in the context of the Anthropocene.

Keywords: Citizen Science, Environmental Education, PISA

Principle And Rationale

From the late 19th century to the 21st century, human activities have profoundly disrupted Earth's ecological balance, ushering in an era termed the Anthropocene. The defining challenges of this epoch—climate change, biodiversity loss, and plastic pollution—threaten the sustainability of life on Earth. Among these issues, plastic pollution stands out due to its ubiquity, persistence, and severe ecological consequences. Poor waste management and excessive reliance on single-use plastics exacerbate global environmental degradation, making the problem a pressing educational priority.

The Anthropocene underscores the power of human activities to reshape Earth's systems—from the fossil-fuel combustion of the industrial revolution to the global proliferation of plastic waste. While plastic use has enabled various economic conveniences, it has also generated persistent waste that infiltrates landfills, rivers, and oceans. In Northern Thailand, such environmental degradation converges with the cross-border haze crisis. For decades, Chiang Mai and Chiang Rai have experienced PM2.5 pollution that exceeds international standards. This air pollution is further exacerbated by cultural and economic practices, including large-scale cremations, waste burning, and agricultural burning—collectively posing serious threats to public health and elevating rates of lung cancer and respiratory diseases (Masters et al., 2021; OECD, 2023).

The Anthropocene also manifests through extreme weather events in Thailand's northern regions. The 2024 flood in Chiang Rai, for example, caused widespread damage to infrastructure, agriculture, and local communities, amplifying economic burdens and health risks. The flood also

generated large volumes of waste—including household garbage, construction debris, and plastic materials—that overwhelmed existing waste management systems. Meanwhile, repeated open-air cremations in some areas, traditionally practiced as part of funerary rites, release additional pollutants into an already compromised atmosphere. Consequently, Northern Thailand has emerged as a vivid case study of the Anthropocene's complexity, illustrating how localized cultural practices and socio-economic factors intersect with global environmental crises.

Educational efforts to address these challenges increasingly focus on equipping students with the competencies to understand, evaluate, and mitigate environmental problems. UNESCO's vision of Education for Sustainable Development (ESD) and the OECD's Programme for International Student Assessment (PISA) 2025 Science Framework converge on this point. Both emphasize action-oriented learning that integrates scientific knowledge with community engagement.

Purposes And Research Questions Of The Study

The purposes of this study were (1) To investigate the effects of implementing the four-step AAAR (Awareness–Anticipation–Action–Reflection) learning cycle on upper secondary students' environmental science competencies, as defined in the PISA 2025 Science Framework. (2) To examine changes in students' environmental science competencies before and after participation in the AAAR-based learning intervention.

Accordingly, this study was guided by the following research question, which asks how the implementation of the four-step AAAR learning cycle influences upper secondary students' environmental science competencies based on the PISA 2025 Science Framework.

Conceptual Definitions

Environmental Science Competencies (ESC)

According to the PISA 2025 Science Framework, three Environmental Science Competencies (ESC) guide the educational preparation of 15-year-olds to face complex socio-ecological challenges (OECD, 2023):

(1) Explaining the impact of human interactions with Earth's systems. This refers to the understanding of the relationships among physical systems, living organisms, and Earth systems. It includes recognizing both the positive and negative impacts of human activities over time, and the ability to comprehensively analyse social, cultural, and economic factors that affect the environment.

(2) Making informed decisions and taking action based on diverse evidence. This refers to the capacity to access and critically evaluate evidence from various sources, and to design environmental solutions using creativity and systems thinking. It also involves civic engagement, goal-setting with people across generations, and working towards environmental restoration and sustainability from the local to the global level.

(3) Demonstrating hope and respect for diverse perspectives. This refers to acting ethically and demonstrating care for living beings, recognizing and addressing social injustices, showing determination in the face of ecological crises, and respecting diverse viewpoints. It includes seeking solutions to restore the environment in inclusive and hopeful ways

Four-Step AAAR Learning Cycle

The Four-Step AAAR Learning Cycle is an iterative learning cycle consisting of Awareness, Anticipation, Action, and Reflection, designed to continuously develop learners' thinking

through intentional and responsible engagement, leading to positive change for self, society, and the environment.

The AAAR cycle is adapted from the OECD Learning Compass 2030 AAR cycle (Anticipation–Action–Reflection) by explicitly adding Awareness as a preparatory step.(Mangkhang, C., 2021)

Conceptual Framework

Based on preliminary findings from surveys, interviews, and student reflections, the study revealed that while students demonstrated awareness of environmental issues, particularly plastic waste, their understanding of systemic environmental impacts and confidence in taking action remained limited. These findings indicated a gap between environmental awareness and meaningful engagement in environmental problem-solving. In response, this study focused on community-based environmental issues, specifically waste management and plastic pollution, as authentic learning contexts. To address this gap, the Four-Step AAAR (Awareness–Anticipation–Action–Reflection) learning cycle was employed as a pedagogical framework to guide students through recognizing local environmental problems, anticipating future consequences, engaging in responsible actions, and reflecting on their learning experiences. Through this iterative learning process, students were expected to develop environmental science competencies aligned with the PISA 2025 Science Framework, including systems thinking, informed decision-making, and student agency.

Figure 1. Research conceptual framework.



Literature Review

The Anthropocene And Environmental Challenges In Education

The Anthropocene highlights the profound influence of human activities on Earth's systems, resulting in complex environmental challenges such as climate change, biodiversity loss, and pervasive plastic pollution (OECD, 2019; White et al., 2024). These challenges are not only global but also deeply embedded in local socio-cultural contexts. In many regions, including Northern Thailand, environmental problems such as plastic waste accumulation, air pollution, and extreme weather events increasingly affect community well-being. Addressing such complexity requires educational approaches that move beyond content knowledge toward

empowering learners to understand and engage with real-world environmental issues (UNESCO-UNEP, 1978; OECD, 2023).

Environmental Science Competencies And The PISA 2025 Framework

In response to the demands of the Anthropocene, the PISA 2025 Science Framework emphasizes the development of Environmental Science Competencies (ESC) that enable students to explain human–environment interactions, make informed decisions based on evidence, and demonstrate respect for diverse perspectives (OECD, 2023). Central to these competencies is the notion of student agency, which involves learners' capacity to participate meaningfully in addressing environmental challenges. Research suggests that while students may demonstrate awareness of environmental problems, they often lack opportunities to develop the competencies and confidence required for informed action (Masters et al., 2021). Consequently, educational frameworks increasingly highlight competency-based and action-oriented learning as essential for environmental education in the Anthropocene.

Action-Oriented Learning For Sustainability

Action-oriented and competency-based learning approaches have been widely advocated within Education for Sustainable Development (ESD) as a means to bridge the gap between awareness and action (UNESCO-UNEP, 1978). Such approaches emphasize authentic learning contexts, community engagement, and reflective practices that allow students to connect scientific knowledge with everyday environmental issues. Studies have shown that context-based and community-oriented learning can support students' systems thinking and ethical awareness, particularly when learning activities are grounded in local environmental challenges (Mangkhang et al., 2021; Masters et al., 2021). However, there remains a need for structured pedagogical models that systematically guide learners from recognizing environmental problems to taking responsible action.

The Four-Step AAAR Learning Cycle

The Four-Step AAAR (Awareness–Anticipation–Action–Reflection) learning cycle builds upon the OECD Learning Compass 2030, which emphasizes anticipation, action, and reflection as key processes for developing learner agency (OECD, 2019). By explicitly incorporating awareness as a preparatory stage, the AAAR cycle provides a structured framework for engaging learners with environmental issues in a holistic manner. The cycle guides students to recognize environmental problems, anticipate future consequences, take informed and responsible action, and reflect on their experiences to inform subsequent learning. This iterative process aligns closely with the goals of environmental science competencies and supports the development of student agency in addressing complex environmental challenges (OECD, 2023).

Taken together, existing literature highlights the need for pedagogical approaches that integrate local environmental contexts, competency-based learning, and action-oriented processes. However, limited empirical research has examined how structured learning cycles such as the AAAR model can be used to foster environmental science competencies within the framework of PISA 2025, particularly in culturally and contextually specific settings. This study seeks to address this gap by implementing the AAAR learning cycle in the context of community-based environmental issues.

Research Design, Scope, And Methods

Variables

- **Independent Variable:** The implementation of the four-step AAAR learning cycle integrated into science learning activities.

- **Dependent Variables:** Students' environmental science competencies as defined by the PISA 2025 Science Framework

Participants

The participants were 24 upper secondary students aged 15–17 years from a public secondary school in Northern Thailand. The school is situated in an area facing environmental challenges such as plastic waste, air pollution, and periodic flooding. Participation was voluntary, and informed consent was obtained from both students and their guardians prior to data collection.

Instruments

Types Of Research Instruments

To address the research objectives, both quantitative and qualitative research instruments were employed.

(1) Cognitive Test

A PISA-aligned cognitive test was developed to assess students' environmental science competencies, with a focus on problem-solving related to plastic pollution and waste management. The test measured students' ability to apply scientific knowledge, interpret data, and propose evidence-based solutions to environmental problems. The instrument was administered before and after the AAAR-based learning intervention.

(2) Environmental Action Scale (EAS)

The Environmental Action Scale, adapted from Alisat and Riemer (2015), was used to assess students' self-reported pro-environmental behaviours and intentions. The scale consisted of Likert-type items addressing daily environmental practices, participation in environmental activities, and willingness to engage in community-based environmental actions.

(3) Qualitative Instruments

Qualitative data were collected to capture students' learning experiences, engagement, and emerging agency throughout the AAAR-based learning activities. Three qualitative instruments were employed: student reflection logs, classroom observations, and student worksheets, all of which were aligned with the four phases of the AAAR learning cycle.

Steps To Create And Validate Research Instruments

This study followed a systematic process to develop and validate research instruments aligned with the research objectives, the Environmental Science Competencies in the PISA 2025 Science Framework, and the Four-Step AAAR learning cycle.

First, the Environmental Science Competencies defined in the PISA 2025 framework were analysed and translated into measurable learning outcomes, which guided the development of all research instruments and learning activities.

Second, both quantitative and qualitative instruments were developed, including a cognitive test of environmental science competencies, an adapted Environmental Action Scale (EAS), and qualitative tools such as student reflection logs, worksheets, and classroom observation protocols. Four AAAR-based lesson plans were also designed as the instructional framework and sources of qualitative evidence.

Third, all instruments and lesson plans were reviewed by experts in science education and curriculum studies to evaluate content validity, clarity, and alignment with the research objectives. Expert feedback was used to revise the instruments.

Finally, the revised instruments were piloted with a small group of students outside the main study, and minor adjustments were made before final implementation for pretest, posttest, and ongoing qualitative data collection.

Data Collection And Analysis

Data Collection

Data were collected throughout the implementation of the four AAAR-based lesson plans using both quantitative and qualitative approaches. Quantitative data were obtained through a cognitive test aligned with the PISA 2025 Science Framework and the Environmental Action Scale (EAS). The cognitive test and EAS were administered to students before and after participation in the AAAR-based learning activities to examine changes in environmental science competencies and pro-environmental behaviours.

Qualitative data were collected concurrently during the instructional intervention. Sources of qualitative data included student reflection logs, classroom observations, and student worksheets produced during the Awareness, Anticipation, Action, and Reflection phases of each lesson plan. These data captured students' learning experiences, engagement, reasoning processes, and emerging agency related to community-based environmental issues, particularly plastic waste management and pollution.

Data Analysis

Quantitative data were analysed using descriptive and inferential statistics. Descriptive statistics, including means and standard deviations, were calculated to summarize students' pretest and posttest scores. Due to the small sample size and non-normal distribution of the data, the Wilcoxon Signed-Rank Test was used to examine differences between pretest and posttest scores. Effect sizes were calculated to determine the magnitude of learning gains following the AAAR-based learning intervention.

Qualitative data were analysed using thematic analysis. Student reflection logs, observation notes, and learning artifacts were systematically reviewed and coded to identify recurring patterns and themes. The analysis focused on themes related to environmental awareness, systems thinking, decision-making, values and responsibility, and student agency. The identified themes were then interpreted in relation to the phases of the AAAR learning cycle and the Environmental Science Competencies defined in the PISA 2025 framework.

To enhance the credibility of the qualitative findings, data triangulation was employed by comparing evidence across multiple data sources, including reflections, observations, and student-produced artifacts.

Research Advantages

This study demonstrates how the Four-Step AAAR learning cycle can be effectively applied to foster environmental science competencies aligned with the PISA 2025 framework. By grounding learning activities in real-world, community-based environmental issues such as plastic waste, the study enhances the relevance of science learning and supports the development of student agency. The findings also provide practical AAAR-based lesson plans that can be adapted by educators to promote action-oriented and competency-based environmental education.

Results

Quantitative Results

Table 1. Descriptive Statistics and Wilcoxon Signed-Rank Test of Environmental Science Competencies before and after

N	Mean of Pre-test	Mean of Post-test	Mean difference	Statistic	P-value	Effect Size	Interpretation
24	78.9	90.8	11.00	300	<.001*	1.00	Large Effect

Note *P-value <.05 interpreted as significant. Effect Size interpreted according to Cohen (1988): .00-.09 Negligible, .10-.29 Small, .30-.49 Medium, ≥ .50 Large

Table 2. Descriptive Statistics and Wilcoxon Signed-Rank Test of Environmental Science Competencies Before and After in Each Dimension

Components of Environmental Science Competencies	N	Mean of Pre-test	Mean of Post-test	Mean difference	Statistic	P-value	Effect Size	Interpretation
1. Explain the impact of human interactions with Earth's systems	24	24.2	30.5	6.00	300	<.001*	1.00	Large Effect
2. Make informed decisions to act based on evaluation of diverse sources of evidence and application of creative and systems thinking to regenerate and sustain the environment	24	48.0	52.8	5.00	246[a]	<.001*	1.00	Large Effect
3. Demonstrate respect for diverse perspectives, and hope, in seeking solutions to socio-ecological crises	24	8.50	10.21	2.00	186[a]	<.001*	0.958	Large Effect
4. Environmental Action Scale								
4.1 Participatory Actions	24	11.7	18.1	7.00	211[a]	0.007	0.664	Large Effect
4.2 Leadership Actions	24	1.13	4.04	4.50	88.5[a]	0.026	0.686	Large Effect

Note P-values <.05 interpreted as significant. Effect Size interpreted according to Cohen (1988): .00-.09 Negligible, .10-.29 Small, .30-.49 Medium, ≥ .50 Large

Quantitative analysis revealed a significant improvement in students' overall environmental science competencies following participation in the AAAR-based learning activities. Post-test scores were significantly higher than pre-test scores, as indicated by the Wilcoxon Signed-Rank Test ($p < .001$). The results demonstrated a large effect size, suggesting that the learning gains were not only statistically significant but also educationally meaningful.

Further analysis by competency dimension showed consistent improvement across all components of environmental science competencies as defined in the PISA 2025 Science Framework. Students demonstrated increased ability to explain the impact of human interactions with Earth's systems, make informed decisions based on evidence and systems thinking, and demonstrate respect for diverse perspectives in addressing socio-environmental issues. In addition, scores on the Environmental Action Scale (EAS) showed statistically significant improvement, indicating positive changes in students' reported pro-environmental behaviours and intentions. Overall, the quantitative findings indicate that the AAAR-based learning intervention supported students' competency development across multiple dimensions.

Qualitative Results

Emerging Themes From Qualitative Data

Qualitative analysis of student reflection logs, classroom observations, and learning artifacts revealed several recurring themes that supported the quantitative findings.

The first theme was environmental awareness and real-life connection. Students demonstrated increased awareness of local environmental issues, such as plastic waste, flooding, and air pollution, and were able to connect these issues to their daily lives and community contexts.

The second theme was systems thinking and future-oriented reasoning. Students increasingly described environmental problems in terms of cause–effect relationships and long-term consequences, including links between waste accumulation, greenhouse gas emissions, and climate-related impacts.

The third theme was values, responsibility, and participation. Many students expressed a growing sense of responsibility toward environmental protection and reported changes in daily behaviours, such as waste separation and reduced plastic use. Some students also shared their learning with peers and family members.

Evidence Of Student Agency

Qualitative evidence further highlighted the development of student agency during the AAAR learning cycles. Some students, particularly those involved in student councils, demonstrated leadership by initiating environmental projects, such as organizing waste separation points and designing community-based campaigns to reduce plastic use. Other students expressed agency through personal behaviour change and future-oriented commitments, as reflected in reflective journals and letters to their future selves. These findings indicate that the AAAR learning cycle supported students in moving beyond awareness toward participation and leadership in environmental action.

Discussion

The findings indicate that the AAAR learning cycle effectively supported the development of environmental science competencies aligned with the PISA 2025 Science Framework. The significant overall improvement suggests that the integration of awareness, future-oriented thinking, action, and reflection created meaningful learning experiences that extended beyond knowledge acquisition toward competency development (OECD, 2023). By engaging students with community-based environmental issues, particularly plastic waste management, the learning process enabled students to connect scientific concepts with real-world contexts, which has been widely recognized as a key condition for effective environmental science education (Stevenson et al., 2013; Wals, 2012).

One important explanation for the observed gains lies in the structure of the AAAR learning cycle itself. The Awareness phase helped students recognize environmental problems as personally and socially relevant, increasing their motivation to engage with scientific content. The Anticipation phase encouraged systems thinking and future-oriented reasoning, allowing students to explore cause–effect relationships and long-term consequences of human–environment interactions, which are central to environmental science competencies in PISA 2025 (OECD, 2023). These phases prepared students to move beyond fragmented understanding toward a more holistic view of environmental challenges characteristic of the Anthropocene. However, differences were observed in students' environmental action and leadership outcomes. Student council members tended to demonstrate stronger gains in leadership-oriented actions compared to their peers. This pattern may be explained by their prior experience in decision-making, collective responsibility, and participation in school governance, which likely enhanced their perceived self-efficacy and ability to translate learning into visible leadership actions (Bandura, 2001). Similar findings have been reported by Alisat and Riemer (2015), who noted that students with previous leadership opportunities are more likely to engage in collective environmental action and advocacy. Most students in the classroom showed growth primarily in participatory and everyday environmental actions, such as changing personal behaviours, engaging in group activities, and sharing environmental knowledge with peers and family members. These outcomes reflect forms of "everyday agency," which are often more accessible and immediately achievable for learners than formal leadership roles (Kollmuss & Agyeman, 2002). Such findings align with research suggesting that environmental engagement typically begins at the individual level before developing into broader social or political action (Chawla & Cushing, 2007). A small number of students demonstrated limited improvement or slight decreases in leadership-related scores. Rather than indicating a failure of the learning intervention, this result highlights that student agency develops at different paces and is influenced by multiple internal and external factors, including motivation, personal values, social norms, and perceived opportunities for action (Ajzen, 1991). Environmental competence should therefore be understood as a dynamic and contextual process rather than a uniform outcome for all learners. Previous studies in environmental education similarly report that increased awareness does not always lead immediately to observable action or leadership, particularly within short intervention periods (Chawla & Cushing, 2007).

Importantly, the qualitative findings suggest that even students who did not show strong quantitative gains in leadership began to recognize their own potential roles in environmental action. Reflective journals and learning artifacts indicated emerging awareness of personal responsibility and future commitments, suggesting that agency may be developing in less visible but still meaningful ways. This supports the view that education for sustainability is inherently a long-term process, shaped by both individual trajectories and socio-cultural contexts (UNESCO, 2020; Wals, 2012).

Overall, these findings highlight that while the AAAR learning cycle can foster environmental action and student agency, differentiated support and extended time may be necessary to engage all learners meaningfully, particularly those who are less inclined toward leadership roles. Providing diverse pathways for participation—ranging from personal behaviour change to collective and leadership-oriented action—may help ensure that all students can develop environmental science competencies in ways that align with their capacities and contexts (White et al., 2024). In this sense, the AAAR learning cycle offers a flexible and promising framework for competency-based, action-oriented environmental science education in the Anthropocene.

Conclusion

This study demonstrates that the Four-Step AAAR learning cycle can effectively support the development of environmental science competencies aligned with the PISA 2025 framework. Through the integration of community-based environmental issues into science learning, students showed improved understanding of human environment interactions, stronger evidence-based decision-making, and emerging forms of student agency. While not all students demonstrated leadership-oriented actions, the findings highlight that environmental agency can develop through diverse pathways, including everyday participation and personal **behaviour** change. The study contributes empirical evidence on how action-oriented and competency based learning can be implemented in upper secondary science classrooms using a structured learning cycle. Future research may extend this approach across longer timeframes or varied contexts to further explore how different forms of agency can be fostered in environmental science education.

Implications

The findings suggest that the AAAR learning cycle can serve as a flexible framework for designing competency-based environmental science learning across various contexts, not limited to waste-related issues. Teachers may adapt this approach to address different environmental challenges relevant to their local settings. In addition, future research may benefit from longer-term implementations to examine how environmental competencies and student agency develop over time.

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Developing Environmental Competencies And Identities Through A Trans-Contextualization Learning Process Using Socio-Scientific Issues

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Rapid socio-environmental change calls for science education that equips students to reason and act on complex sustainability challenges. This study examined the effectiveness of a Trans-Contextualization Learning Process Using Socio-Scientific Issues (TCUSSI) in strengthening Grade 8 students' environmental competencies (EC) and environmental identities (EI) through two SSI contexts—fossil fuels and food waste—sequenced across micro (personal), meso (local), and macro (global) levels. Grounded in the PISA 2025 Science Framework, the intervention engaged learners in evidence-based reasoning, systems thinking, and reflection on civic responsibility. Participants were 32 Grade 8 students in Lampang Province, Thailand. A mixed-methods design employed an Environmental Competencies Test (ECT) adapted from PISA-style tasks and an Environmental Identities Questionnaire (EIQ) based on Clayton (2003), complemented by open-ended responses and reflective journals. Findings indicated significant gains in all EC components and in four of five EI components, with large effect sizes, and a moderate post-intervention correlation between EC and EI. Qualitative evidence corroborated increased awareness, local–global sustainability linkages, and emerging youth agency, while highlighting challenges in quantitative reasoning and behaviour–intention alignment. Overall, TCUSSI demonstrates strong potential as a contextually grounded socio-scientific pedagogy for lower secondary sustainability education.

Keywords: Trans-Contextualization Learning Process Using Socio-Scientific Issues, Environmental Competencies, Environmental Identities

Introduction

Rapid societal changes in science, technology, economics, and the environment have produced interconnected impacts at both local and global levels. In recent decades, fluctuating economies, aging populations, disease outbreaks, borderless information exchange, and escalating climate crises underscore the urgent need for awareness and preparedness (Holbrook et al., 2022). In this context, education is critical for equipping young people to respond to current and future challenges. Contemporary educational goals increasingly emphasize holistic well-being by integrating health, civic engagement, social connection, and environmental stewardship (OECD, 2023), and the OECD (2019) highlights that such outcomes support the development of active global citizens who can contribute to sustainable development and social responsibility.

Science education, in particular, must prepare learners to engage with complex socio-environmental problems by strengthening their capacity to navigate multifaceted issues (Sadler & Zeidler, 2009). Many contemporary challenges—such as nuclear risks, genetic dilemmas, global warming, and resource depletion—are inherently socio-scientific because they require scientific understanding alongside ethical and social judgment (Chowdhury, 2022). As a result, educators increasingly adopt socio-scientific issues (SSI)—controversial topics that connect social contexts with scientific inquiry—to foster evidence-based argumentation and responsible decision-making (Presley et al., 2013). A key pedagogical support for SSI is context-based learning, which anchors scientific ideas in familiar situations and gradually expands learning

toward broader contexts (Chowdhury, 2022; Holbrook et al., 2022). This staged movement across micro (personal), meso (local), and macro (global) contexts is also consistent with the OECD's PISA 2025 Science Framework (OECD, 2023).

In addition, responding to environmental crises such as climate change requires attention not only to what students know and can do, but also to how they perceive their relationship with nature. EI influences whether learners see themselves as part of interconnected ecosystems and engage in ecological problem-solving (Clayton, 2003). Therefore, integrating SSI with identity-oriented and contextualized learning may support the development of both EC and EI that underpin environmentally responsible citizenship.

In response to these needs, this study examines the effectiveness of TCUSSI for lower secondary students. The study investigates whether TCUSSI strengthens Grade 8 students' EC and EI and examines the relationship between EC and EI following participation in the TCUSSI intervention among 32 Grade 8 students in a district secondary school in Lampang Province, Thailand. Accordingly, the study addresses two research questions:

(1) To what extent does the TCUSSI intervention enhance Grade 8 students' EC and EI?

(2) What is the relationship between EC and EI among students after participating in the TCUSSI intervention?

Theoretical Background

SSI are open-ended problems in which scientific knowledge intersects with ethical, social, and political considerations. SSI-based learning is therefore a key approach for developing evidence-based reasoning and responsible decision-making in science education (Sadler & Zeidler, 2009). A persistent limitation, however, is that SSI learning can remain confined to classroom argumentation without systematically connecting students' reasoning to lived experiences or to wider societal and global realities. This study therefore adopts TCUSSI, which structures learning across micro (personal), meso (local/community), and macro (global) contexts so that learners revisit the same issue with increasing systemic complexity and civic relevance (Holbrook et al., 2022). This sequencing follows the logic of context-based learning—starting from familiar situations and extending understanding across broader contexts—while providing a coherent trajectory for sustained meaning-making (Chowdhury, 2022). In this study, TCUSSI is enacted through the unit Our World using fossil fuels and food waste as SSI contexts and implemented through four stages: contextualization, de-contextualization, re-contextualization, and trans-contextualization (Holbrook et al., 2022).

Within TCUSSI, the study targets two complementary outcomes—EC and EI. EC represent students' capacity to understand and respond to socio-ecological challenges in the Anthropocene (Ketsing, 2023). Consistent with the PISA 2025 Science Framework, EC are defined as the ability to explain human interactions with Earth's systems, make informed decisions using diverse evidence and systems thinking, and demonstrate respect for diverse perspectives and hope when addressing socio-ecological crises (OECD, 2023). Developing EC requires learners to interpret information and justify decisions through evidence-based and systems-oriented reasoning, which aligns with competence development in SSI-based learning (Presley et al., 2013).

EI complement competence-based outcomes by explaining how learners perceive their relationship with nature and their role within socio-ecological systems. EI are defined as how individuals perceive and define their relationship with nature, encompassing the importance of personal interactions with nature, self-identification within ecosystems, commitment to sustainability, positive emotions toward nature, and autobiographical memories of engaging with

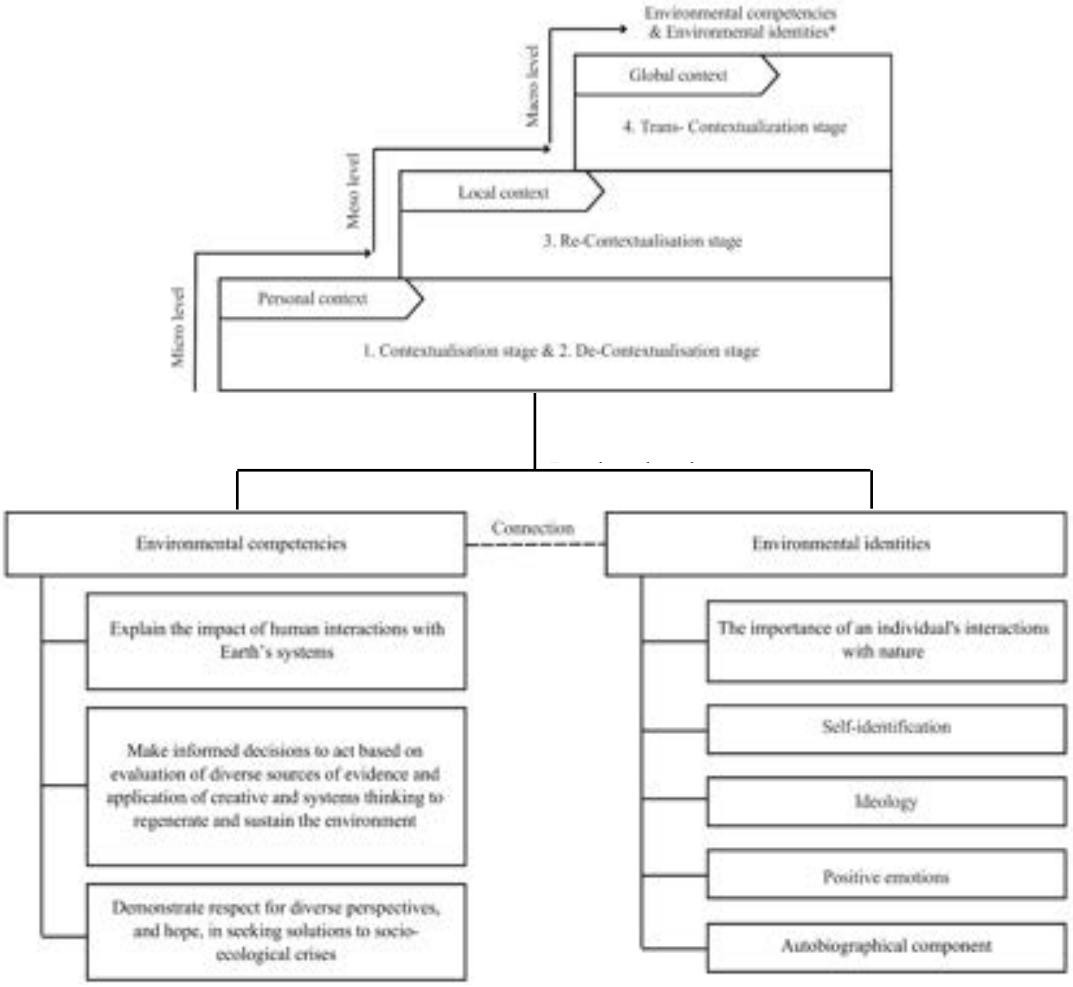
nature (Clayton, 2003). Empirical work suggests that stronger EI are associated with pro-environmental attitudes and behavioural change, particularly when learning invites reflection and connects environmental issues to students' sense of self (Blatt, 2013).

Prior studies indicate that SSI and contextualized learning can deepen understanding, improve argumentation, and foster ethical awareness (Tal & Kedmi, 2006), while staged contextual movement can support learners' agency in addressing both everyday and global dilemmas (Sadler et al., 2016). Trans-contextual learning further extends this potential by linking local concerns to global sustainability challenges and strengthening orientations aligned with active informed citizenry (Chowdhury et al., 2020; OECD, 2019). Yet, evidence remains limited on whether trans-contextual SSI learning can simultaneously strengthen EC and EI and bring these outcomes into closer alignment. This study therefore examines TCUSSI as a coherent theoretical approach for investigating growth in EC and EI among lower secondary students and for exploring whether the relationship between EC and EI becomes stronger following the intervention.

Conceptual Framework

The conceptual framework of this study, outlining the expected linkage between TCUSSI and the concurrent development of EC and EI, is presented in Figure 1.

Figure 1. Research conceptual framework.



This study conceptualizes TCUSSI as a mechanism that integrates SSI-based learning across micro–meso–macro contexts to support the concurrent development of EC and EI. As students progress from personally meaningful situations to local and global sustainability challenges, they are expected to strengthen their ability to explain human–Earth system interactions and make evidence-informed decisions (EC), while also deepening their sense of connection, responsibility, and self-identification in relation to nature (EI). This pathway illustrates how trans-contextual sequencing within TCUSSI—implemented through SSI learning in Our World—is theorized to foster integrated growth in EC and EI.

Methodology

Participants

Participants were 32 Grade 8 students from a district-level secondary school in Lampang Province, Thailand, selected purposively to reflect typical academic backgrounds and local living contexts.

Instruments

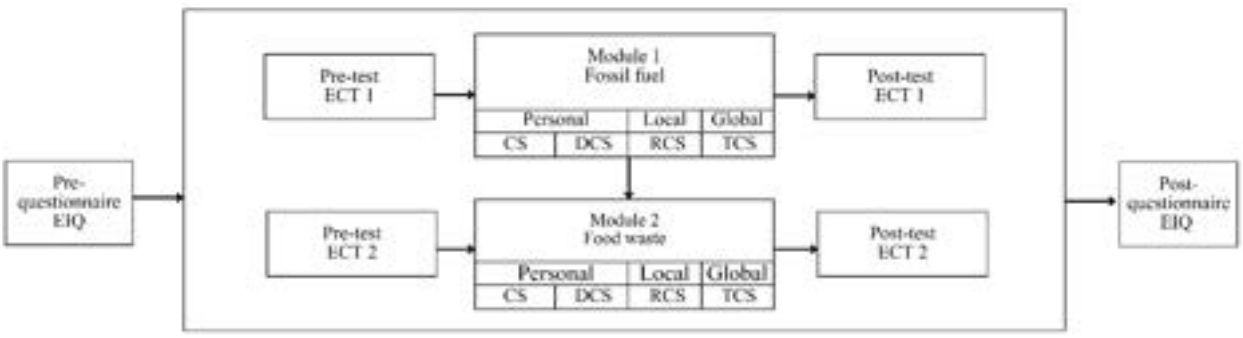
This study used three instruments. EC were assessed using an Environmental Competencies Test (ECT) consisting of two parallel 3-item forms (fossil fuels; food waste) adapted from PISA-style tasks (12 points per form; 24 points in total). EI were measured using a 24-item Environmental Identities Questionnaire (EIQ), a 5-point Likert scale adapted from Clayton (2003). Reflective journals were used to capture students' evolving ideas and experiences.

All instruments were expert-reviewed for content validity and alignment, and items were screened using IOC (≥ 0.67; Turner & Carlson, 2003). While all six ECT items met the criterion, Item 3 in both forms was revised from multiple-choice to open-ended to better elicit real-world actions aligned with EC. EIQ items below the IOC criterion were removed and wording refined for Grade 8 appropriateness. The EIQ demonstrated excellent internal consistency in a pilot test ($\alpha = .927$; Taber, 2018).

Data Collection And Analysis

Data were collected across two TCUSSI modules. For Module 1 (Fossil Fuels), students completed the EIQ and ECT pre-test, followed by the ECT post-test after 6 class hours. For Module 2 (Food Waste), students completed the second ECT pre-test and post-test after another 6 class hours, and the EIQ was administered again after both modules. Quantitative data were analysed using descriptive statistics, Wilcoxon signed-rank tests, and Spearman's rho. Qualitative data from open-ended ECT responses and journals were thematically coded (Creswell, 2014).

Figure 2. Data Collection Procedure.



Ethical Considerations

This study was approved by the Chiang Mai University Research Ethics Committee (CMUREC No. 68/144; COA No. 165/68) through an expedited review process. All participants and their legal guardians provided informed consent after receiving detailed information about the study's objectives, procedures, and their right to withdraw at any stage without penalty. To ensure confidentiality, all data were collected and reported in aggregated form, and no personally identifiable information was disclosed. Photography or video recordings were limited to group learning activities and were conducted only with explicit permission from participants and their guardians. In accordance with institutional research ethics guidelines, all research materials and data will be securely stored and destroyed within three years after publication.

Results

Effects Of The TCUSSI Learning Process On Grade 8 Students' EC

Components of EC	Pre-test		Post-test		Mean difference	Statistic	p-value	Interpretation	Effect Size	Interpretation
	Mean	S.D.	Mean	S.D.						
1. Explain the impact of human interactions with Earth's systems	4.09	1.47	5.44	1.52	1.50	370[a]	<.001*	Significant	.699	Large Effect
2. Make informed decisions to act based on evaluation of diverse sources of evidence and application of creative and systems thinking to regenerate and sustain the environment	7.28	2.84	12.75	2.65	6.00	488[a]	<.001*	Significant	.968	Large Effect
3. Demonstrate respect for diverse perspectives, and hope, in seeking solutions to socio-ecological crises	15.10	3.17	16.40	2.73	2.00	224[a]	.009*	Significant	.620	Large Effect

Table 1. Descriptive Statistics and Wilcoxon Signed-Rank Test of EC before and after TCUSSI Participation

Note: 1. *p < .05 2. Effect size interpreted according to Cohen (1988): .00 – .09 negligible, .10 – .29 small, .30 – .49 medium, ≥ 0.50 large

After participating in TCUSSI, students showed significant improvement in all three EC components. They demonstrated a stronger understanding of human impacts on Earth's systems, with a large effect size. The greatest gain was in their ability to make informed and creative decisions for sustainability, which showed a large effect. Respect for diverse perspectives and hopeful engagement with socio-ecological problems also increased significantly. Overall, TCUSSI produced strong, meaningful gains in students' environmental competencies.

Influence Of TCUSSI On Grade 8 Students' EI

Table 2. Descriptive Statistics and Wilcoxon Signed-Rank Test of EI before and after TCUSSI Participation.

Components of EI	Pre-test		Post-test		Mean difference	Statistic	p-value	Interpretation	Effect Size	Interpretation
	Mean	S.D.	Mean	S.D.						
The importance of an individual's interactions with nature	13.50	3.10	14.50	2.27	2.00	142[a]	.014*	Significant	.661	Large Effect
Self-identification	17.30	3.94	18.60	3.07	1.50	285[a]	.005*	Significant	.621	Large Effect
Ideology	13.2	2.91	14.40	2.56	2.00	233[a]	.018*	Significant	.553	Large Effect
Positive emotions	17.80	4.14	18.60	3.46	1.00	230[a]	.169	Not Significant	.311	Medium Effect
Autobiographical component	7.09	1.89	7.59	1.56	1.00	190[a]	.038*	Significant	.498	Medium Effect

Note: 1. *p < .05 2. Effect size interpreted according to Cohen (1988): .00 – .09 negligible, .10 – .29 small, .30 – .49 medium, ≥ 0.50 large.

TCUSSI led to significant improvement in four of the five EI components. Students strengthened their sense of connection to nature, environmental self-identification, and ideology, all with large effect sizes. The autobiographical component also increased significantly with a moderate effect. Although positive emotions toward nature did not significantly change, it still showed a modest improvement. Overall, TCUSSI effectively enhanced students' identity-based engagement with the environment.

Relationship Between EC And EI Following TCUSSI Participation

Before TCUSSI, EC and EI were not significantly related. After the intervention, the correlation became moderate and statistically significant, indicating that students who developed stronger environmental identities also demonstrated higher environmental competencies. This suggests that TCUSSI fosters a connected growth between what students know/do and who they perceive themselves to be regarding the environment.

Variables	ρ (Spearman's rho)	Test Statistic	p-value	Interpretation
EI (Pre-test) and EC (Pre-test)	.21	1.17	.25	Not Significant
EI (Post-test) and EC (Post-test)	.46	2.86	.01*	Significant

Table 3. Spearman's Rank Correlation between EC and EI Scores before and after TCUSSI Participation.

Note: *p < .05

At the same time, the students proposed diverse solution pathways. They emphasized reducing and phasing out fossil fuel use, shifting to renewable and clean energy (solar, wind, biomass, hydrogen), conserving energy in daily life, and adopting circular-economy practices such as recycling, reusing, repairing, composting, and reprocessing leftovers. They also valued local wisdom in food preservation as a way to extend shelf life and reduce food waste. Yet, their proposals were mostly qualitative: students rarely used quantitative evidence such as carbon footprints or cost–benefit considerations, and they seldom analysed trade-offs among different options. Moreover, while many expressed intentions to "eat just enough", "finish all food", save electricity, use cloth bags, or choose sustainable travel modes, some students admitted that they were unlikely to change their behaviour despite understanding the impacts, revealing a gap between awareness and action.

Across the reflections, worksheets, and creative products, the data strongly indicate the emergence of environmental identity and youth agency. Students described feelings of peace, happiness, and attachment when in natural places and expressed a desire to protect these environments. Experiences of environmental degradation, especially around the coal mine, triggered concern and a sense of injustice, which motivated them to "take care of nature together". Through letters to their past and future selves and Fossil Fuel Comics, they showed guilt about past behaviours but also a clear commitment to becoming people who use energy wisely and live more sustainably. They increasingly recognized that environmental problems require shared responsibility and systemic change, not just individual actions. Students called for collaboration among government, communities, schools, and households; for listening to community voices; for transparent monitoring of large projects; and for stronger policies and laws, inspired by international examples such as France's anti–food waste legislation. At the same time, they realistically acknowledged challenges in the transition to 100% renewable energy, including technological, financial, infrastructural, and political–economic constraints.

Conclusion And Discussion

The findings indicate that TCUSSI substantially enhanced students' environmental learning across cognitive, affective, and identity-based dimensions. By engaging students with SSI contexts grounded in everyday life, the intervention enabled them to situate global sustainability challenges within local realities—particularly fossil fuels, coal mining, food systems, and carbon footprints—thereby strengthening the relevance and coherence of their learning experiences. Quantitative results show significant improvements across all EC components with large effect sizes, including clearer understanding of human–Earth system interactions and stronger evidence-based, creative, and systems-oriented decision-making for sustainability. EI also increased significantly in four of five components, especially connection to nature, environmental self-identification, and ideology. However, positive emotions toward nature did not show a clear change. This may reflect a ceiling effect, as students already held relatively positive feelings

toward nature prior to the intervention, and because affective development often requires longer-term, repeated, and more embodied experiences in natural settings than a classroom-based SSI sequence can typically provide. Importantly, the moderate post-intervention correlation between EC and EI—absent at pre-test—suggests that TCUSSI aligned students' developing competencies with their environmental self-concept.

These outcomes provide empirical and theoretical support for TCUSSI as a response to limitations reported in context-based and SSI-oriented science education. Real-world contexts may enhance relevance yet remain bounded within classroom understanding, with weak links to societal engagement (Fensham, 2009; Swirski et al., 2018). Likewise, SSI pedagogy can strengthen argumentation and ethical reasoning but still struggle to bridge classroom decision-making and real-world action (Sadler, 2011; Zeidler et al., 2009). In contrast, the findings suggest that explicit trans-contextualization—sequencing learning across micro (personal), meso (local), and macro (global) contexts—helps address this gap by enabling learners to revisit the same SSI with increasing systemic complexity and civic relevance. Across contexts, students increasingly framed fossil fuels and food waste as interconnected socio-ecological systems requiring collective responses, supporting the shift from science through education toward education through science, where societal relevance and citizen engagement become central outcomes (Holbrook & Rannikmäe, 2007; Holbrook, 2010).

The significant gains in EC, particularly in evidence-based and creative decision-making, indicate that TCUSSI operationalizes key competencies emphasized in the PISA 2025 Science Framework, including systems thinking and informed action in the Anthropocene (OECD, 2023). This addresses concerns that SSI reasoning may remain largely qualitative or opinion-based, with limited integration of evidence and systemic analysis (Hodson, 1999; Yacoubian & Khishfe, 2018). Qualitative evidence further corroborates students' internalization of SSI related to fossil fuel use, air pollution, coal mining, food waste, and carbon-intensive diets, alongside proposed solutions such as renewable energy, energy conservation, circular-economy practices, traditional food preservation, and community-based waste management. However, many responses still lacked quantitative evaluation and explicit trade-off analysis, underscoring the need for stronger scaffolding in analytic reasoning.

A further contribution lies in clarifying the relationship between competence development and identity formation. Although EI has been widely recognized as influencing pro-environmental concern and behaviour (Clayton, 2003; Green et al., 2016), empirical work connecting identity development to competence-based science frameworks remains limited. The post-intervention EC–EI correlation suggests that TCUSSI may better integrate these outcomes, responding to calls to connect identity and competence that have often been treated as parallel but weakly related in environmental education (Hinds & Sparks, 2008; Lou & Li, 2021). Qualitative findings reinforce this interpretation through students' expressions of emotional attachment to nature, heightened moral concern, and growing responsibility, consistent with strengthened EI.

At the same time, qualitative data reveal an awareness–action tension: some students recognized environmental impacts yet expressed reluctance to change behaviour. Rather than signaling failure, this pattern reflects socio-scientific reasoning that acknowledges technological, economic, and political constraints on sustainability transitions, consistent with accounts of mature SSI engagement emphasizing uncertainty, trade-offs, and power relations (Sadler, 2011; Levinson, 2018). In this sense, TCUSSI appears to support not only action-oriented thinking but also adaptive capacity, which is crucial under rapid socio-environmental change.

Overall, TCUSSI proved effective in strengthening EC, EI, and early systems thinking, while addressing a key research gap by showing how trans-contextual SSI learning can integrate

competencies, identity, and emerging agency within a coherent pedagogical model. Consistent with active informed citizenry, the findings suggest that TCUSSI moves beyond preparing informed individuals toward fostering learners who can locate themselves within complex socio-environmental systems and reflect critically on their roles in societal transformation (Holbrook, 2010; Chowdhury et al., 2020). Future work should strengthen scaffolding for quantitative reasoning, systemic trade-off analysis, and behaviour–intention alignment to deepen students' capacity to engage meaningfully with complex socio-scientific issues.

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Section: Getting Engaged With Nature And Environment

ESERA 2025 Copenhagen

Children's Connection to Nature: Do Forest Schools Make a Difference?

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In times of global environmental unsustainability, there is growing advocacy for reconnecting people, especially children, with nature towards countering current environmental problems. With increasingly urban lifestyles, people spend most of their time indoors, leading to a growing disconnection from nature. Children, especially, are losing opportunities to be outside and engage in nature. Contemporary environmental issues are linked to this human-nature disconnect. Forest Schools (FS) hold significant potential to address these issues. A tenet of FS is that learning in nature is not sporadic but regular and continual. Correspondingly, one objective of FS is cultivating connection-to-nature and fostering a sense-of-concern and responsibility for the environment. This study addresses a gap in empirical literature - do children attending FS differ in their connection-to-nature than those who learn in traditional non-Forest school settings? Employing three different tools (previously used with children)- a close ended questionnaire and two visual tools, this studied compared cognitive, affective, experiential, and behavioural aspects of the psychological construct connection-to-nature between primary schoolchildren who learn in two FS and those who learn in a traditional non-FS. Results clearly show that FS children have a stronger emotional connection-to-nature, they comprehend more the importance of the natural environment and have greater intention for pro-environmental behaviours compared to their traditional school peers. FS children identify nature as part of their personal identity in contrast to non-FS children, and wild nature stands out as their most preferred place for playing. This study provides direct evidence that learning in FSs enhances children's connection to nature.

Keywords: Forest School, Connection to Nature, Primary School Children

Introduction

In the context of global environmental unsustainability, fostering a connection between people and nature has become increasingly critical towards countering current environmental problems. With increasingly urban lifestyles in an industrialized technology-driven world, people spend the bulk of their time indoors, leading to a growing disconnection from nature. Children, especially, are losing opportunities to be outside and engage in nature. Contemporary environmental issues are linked to this disconnection from nature. Ecologist Aldo Leopold, already in 1949, argued that when individuals perceive the "land" as a commodity rather than identifying themselves part of it, respect for the environment diminishes, ultimately leading to its careless exploitation. Research supports that nature-connectedness is a critical psychological driver providing intrinsic motivation for environmentally responsible behaviour in adults (Frantz & Mayer, 2014; Nisbett et al., 2009) and in children (Otto & Pensini, 2017).

Nature connectedness (also termed connection to nature or nature connection) is a multidimensional psychological construct illustrating positive human-nature relationships, with cognitive, affective, experiential and behavioural aspects (Frantz & Mayer, 2014; Nisbett et al., 2009; Schultz, 2002).

Since connection-to-nature can be nurtured through direct interaction with nature, frequent and prolonged immersion in nature is more likely to influence ecological behaviours compared to

brief and sporadic encounters (Otto & Pensini, 2017). More access and experience of young people in nature reflects higher levels of nature connection (Barrable & Booth, 2020; Cheng & Monroe, 2012), while lower levels of childhood nature connection are related to increased time indoors, with digital entertainment (Larson et al., 2019). Two main driving forces for connecting children with nature are the importance for their wellbeing (O'brien, 2009) and environmental conservation, the latter grounded in connection-to-nature as a motivational factor to pro-environmental behaviour.

This study addresses the role of Forest Schools (FS) in enhancing children's connection-to-nature. Forest School Education is a distinctive educational approach that utilizes forest/woodland settings as an immersive environments for deeper more holistic learning experiences. As a specific subfield within outdoor environmental education, FS supports the overarching goals of environmental education (Grimm et al., 2011; Tal et al., 2023). The FS approach builds on the wide range of cognitive, affective, physical, interpersonal and behavioural benefits of learning outdoors (O'brien, 2009). A basic principle of this approach is that learning within natural environments occurs regularly and repeatedly, and is linked to the national curriculum (FSA, 2021; O'brien, 2009). With increasing concerns regarding children's disconnect from nature and the implications of the consequential lack of familiarity and appreciation of the natural world on their likeliness to care for their world and adopt pro-environmental behaviours, FS hold significant potential to address these issues. Emerging from the Scandinavian tradition of outdoor kindergartens, FSs have gained popularity in primary schools across Europe and North America (Harris, 2017).

An objective of FS is to cultivate a connection-to-nature and foster a sense-of-concern and responsibility for the environment (Grimm et al., 2011). Hence, while it is presumed that FS will enhance children's connection-to-nature, empirical evidence that learning in a FS promotes this attribute is lacking. Although studies have investigated children's connection-to-nature (Chawla, 2020; Cheng & Monroe, 2012; Larson et al., 2011; Otto & Pensini, 2017; Richardson, 2019), evidence directly linking FS participation and increased nature connectedness is wanting. This study responds to this gap. It explored whether children attending a FS differ in their connection-to-nature compared to those in traditional non-Forest school settings. This study forms part of a broader research examining the FS approach in Israel. The study was conducted in two of the three FS that existed in Israel.

Methodology

Research Settings And Participants

The study was conducted in three primary schools- two FSs (further termed YR and BY) and one traditional non-Forest School (further termed NH), all situated in rural communities and serving communities with similar socio-economic attributes. The participating FSs comprise two of the three existing FSs in the country. In them learning is fully outdoors, in nearby woodland adjacent to a local nature reserve. They are relatively young, growing schools, and consequently are smaller than the reference school. Participating students were from middle (3rd grade, 8-9 years old) to upper grades (5th grade, 10-11 years old) ensuring the study is conducted with children who have experienced learning in a FS. All students in each grade participated, except for the reference fifth grade, in which half of the classes participated. The research population comprised 104 FS students and 87 non-FS students.

Instrumentation

The study employed three instruments that have been found suitable for children.

Questionnaire

The questionnaire comprised two validated questionnaires previously employed with children. (1) The Nature Connection Index (NCI) (Richardson, 2019) addresses different aspects of a sense-of-connectedness to nature; (2) The Children's Environmental Perception Scale (CEPS) (Larson et al., 2011) assesses two components reflecting ecological appreciation and environmental concern: Eco-affinity (interest in nature and intentions to engage in pro-environmental behaviour) and Eco-awareness (cognitive grasp of environmental issues related to ecological sustainability). The questionnaire was translated into Hebrew and slightly adapted for Israeli children. Internal reliability of the whole questionnaire and its sections ranged between 0.84-0.93.

Inclusion Of Nature In Self (INS)

This visual scale (Shultz, 2002) assesses the extent to which individuals identify nature as part of their personal identity by a series of two overlapping circles- "Self"/"Nature". The greater the overlap, the greater the inclusion-of-nature-in-self. Participants selected the extent of overlap that best describes them.

Photographs Of Play Settings

This visual tool, adapted from Shepardson (2005), employs a series of five photographs of children playing in different settings ranging from indoor and technological to untamed natural environment: indoor digital games, urban street, urban playground, cultivated woodland, natural woodland. Participants selected in which settings they prefer most to play and feel most comfortable.

Data Collection

The researcher administered the tools accompanied by the class teacher. In the reference school, the tools were administered in the classroom, in the forest schools - outside.

Data Analysis

Due to the small number of students in each grade in the FSs, data were aggregated from the three levels. ANOVA and Scheffe Post Hoc examined differences among students from each school. For the visual tools, the frequency of each option was calculated and Chi squared for independence examined for differences in the distribution among students from each school.

Ethics Statement

The study was approved by the Chief Scientist, Ministry of Education. Data collection from the students received parental approval and was fully coordinated with the school administration.

Results

Connection-To-Nature Questionnaire

No significant differences were found between the two FS. FS students scored higher in all connection-to-nature measures and standard deviations were smaller (Table 1). They exhibit stronger emotional connection-to-nature (NCI), comprehend more the importance of the natural environment (Eco-Awareness) and have greater intention for pro-environmental behaviours (Eco-Affinity) compared to their peers in the traditional school.

Table 1. Comparison of connection-to-nature variables between children who learn in FS and those who learn in a traditional school.

Connection-to-nature variable	Mean ± SD		F-value	Significance
	Forest Schools (n=85)	Reference School (n=94)		
NCI	3.75±1.01	3.30±1.28		
Eco-Awareness	4.58±0.84	3.92±1.34		
Eco-Affinity	3.94±1.13	3.31±1.42		
Total mean	4.10±1.07	3.51±1.39	33.74	<.001

Inclusion Of Nature In Self

No differences were found in the extent of inclusion-of-nature-in-self between the FSs. FS children identify nature as part of their personal identity: the greater the self/nature overlap, the higher the percentage of children that chose this option. In contrast, children in the traditional non-FS displayed a distribution among options, with no clear trend in the extent to which they include nature as part of their self-identity (Table 2).

Table 2. Comparison of the distribution (%) of choices of Inclusion-in-Self (INS) between children in FSs and the traditional school.

Group	Self/Nature fully separated	Self/Nature small overlap	Self/Nature extensive overlap	Self/Nature fully overlapped	Chi Square test		
					Chi value	df	significance
FSs	2.30	14.94	37.93	44,83	22.72	3	<.001
Ref school	15.38	31.73	17.31	35.38			

Preferred Play Environment

No differences were found in the preferred play settings between the FSs. FS children showed significant differences from their traditional school peers in their preferred play settings. Untamed nature stood out as the favoured play settings of FS children (>70%), while preference for playing in nature and indoor multimedia games was similar in non-FS children (Table 3).

Discussion

There is growing advocacy for reconnecting people, especially children, with nature to promote environmental sustainability. FS– long-term outdoor learning settings- have gained recognition as a significant way to foster this connection. This study addresses a gap in the research concerning the influence of FS on children's connection-to-nature. To tap into the different psychological aspects of connection-to-nature, this study employed multiple visual and textual tools. Despite the limited sample size (reflecting small numbers of children in the participating schools), the findings highlight that FS children exhibit a deeper and more significant connection-to-nature than their traditional school counterparts. FS children demonstrate a stronger emotional bond and sense of belonging to the natural world (NCI). They include nature-in-self reflecting

that their connectedness encompasses care and commitment to nature (Schultz, 2002). They express more cognitive understanding of the importance of nature (Eco-Awareness) and greater intention for involvement in pro-environmental action (Eco-Affinity). These findings align with research indicating that connection-to-nature promotes pro-environmental behaviours in children (Otto & Pensini, 2017). Expectedly, both groups enjoy multimedia games, which are identified a key factor associated with declining nature-based outdoor time for youth (Larson et al., 2019), but FS children clearly prefer playing outdoors in wild nature to indoor multimedia entertainment. In conclusion, this study provides direct evidence that learning in a FS enhances children's connection-to-nature.

Table 3. Comparison of the distribution (%) of the participants' preferred play settings between children in FS and those in the traditional school.

Group	Digital game indoors	Urban street	Urban play-ground	Cultivated woodland	Natural woodland	Chi Square test		
						Chi value	df	significance
FSs	16.09	2.30	8.05	2.30	71.26	15.21	4	.004
Ref-school	38.46	2.88	11.54	2.88	44.23			

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Empowering Pupils To Explore Urban Environments. Identifying Contexts For Environmental Sensing Using Non-Functional Prototyping.

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When engaging in outdoor activities in public places, school pupils are exposed to environmental conditions such as heat and noise, as well as pollutants like particulate matter. This work investigates how school pupils can be made aware of these conditions, learn about their background, and reflect on the connection between outdoor activities and environmental conditions by enabling children to design non-functional, context-based environmental sensor artifacts in a three-stage workshop. A participatory workshop setting is introduced that identifies and describes the contexts of school pupils' outdoor activities as well as relevant measured variables in these contexts. Furthermore, school pupils design prototypes for environmental sensor artifacts using creative materials such as fabrics, cardboard, and dummy electronic components. Results from three workshops with 57 pupils reveal contexts in which environmental sensing can be applied, and environmental education can be connected to their personal interests and daily routines. The workshop results include non-functional prototypes as the basis for further design steps toward functional environmental sensor artifacts. Feedback from practitioners and experts provides valuable insights into enhancing the workshop setting and its materials. The study contributes a structured participatory design approach that bridges pupils' lived outdoor practices with environmental sensing concepts in lower secondary STEAM education. The outcome of our approach demonstrates how environmental education and the impact of environmental conditions on the realities faced by school pupils can be applied in STEAM education.

Keywords: Environmental Education, Classroom Research, STEM Education

Introduction

Climate change and its negative impacts on the environment are among the most significant challenges facing the world today. This particularly affects urban areas, where, for example, air pollution, higher anthropogenic waste, heat, and poor outdoor thermal comfort lead to overheating and poor air quality (IPCC, 2023). Children are directly exposed to these pollutants when being active in public spaces. This work investigates how pupils can be empowered to explore urban areas they frequently use by identifying contexts of outdoor activities and measured variables relevant to 10-14-year-old children. Therefore, non-functional environmental sensor artifacts are designed in participatory classroom workshops. The work is aligned with Austrian educational goals, where pupils learn to describe applications of technology in the environment and society using interdisciplinary examples and consider their relevance for social groups and cultural contexts (BGBl., 2022), the European sustainability competence framework GreenComp (Bianchi et al., 2022), as well as with the United Nations Sustainable Development Goal 13.3, which aims to improve education and awareness-raising on climate change mitigation (United Nations, 2016). The Austrian curriculum does not include subject-specific computer science teaching at this age. STEAM subjects provide the educational foundation for this work, as they combine science, technology, engineering, and the arts. Many educational materials, projects, products, and technologies have emerged in recent years to support pupils in learning to code (*Scratch - Imagine, Program, Share*, 2024), assemble robots (*Micro*, 2024), and experiment with

environmental sensors (*senseBox*, 2023). The focus of these solutions is on helping children understand complex technology. While numerous educational tools introduce pupils to environmental sensors, little is known about how pupils themselves contextualize environmental sensing within their everyday outdoor practices. This study addresses the gap by engaging pupils as active designers of environmental sensing artifacts grounded in their own outdoor activities. Through participatory, non-functional prototyping, pupils identify relevant contexts, environmental influences, and measurable variables connected to their everyday experiences in urban environments. To better understand how environmental sensing can be meaningfully embedded in pupils' lived experiences, this study investigates the following research questions:

RQ1: How do pupils conceptualize the relationship between their everyday outdoor activities, perceived environmental conditions, and measurable environmental variables within a participatory design process?

RQ2: How are these conceptualizations materialized in pupils' non-functional prototypes of environmental sensing artifacts?

Theoretical framework

Contextual Design (CD) integrates user-centred techniques into the development of software and hardware systems and, therefore, focuses on users and their practices (Beyer & Holtzblatt, 1997). CD aims to design "a new and better way for users to live their lives, achieve their intents, touch the people that matter to them, and perform their activities by introducing better tools and systems." (Holtzblatt & Beyer, 2015). While CD ensures that the resulting artifacts are aligned with the user's context, *Participatory Design* (PD) integrates users as contributors to the entire design process. The design process is realized as a partnership between implementers and users (Schuler & Namioka, 1993). Musaeus et al. (2024) apply PD to design learning tools involving teachers, researchers, and developers to overcome challenges in computing education in high schools. Morais et al. (2022) present a theoretical model for children's participation, including typologies and roles in a PD process. The model serves as a theoretical foundation, supporting the planning of activities and methods in the design process. Iivari et al. (2024) follow a PD approach that includes activism education to enable PD that matters, meaning the PD process must address significant societal issues that matter to people. *Participatory urbanism* describes the involvement of citizens in research activities and "promotes new styles and methods for individual citizens to become proactive in their involvement with their city, neighbourhood, and urban self-reflexivity" (Paulos et al., 2008). Participatory urbanism enables a better understanding of, e.g., air quality through the use of low-cost hardware and higher-resolution data for an area (Miskell et al., 2017). Benavides Lahnstein et al. (2022) investigated young people's participation in citizen science programs and called for enhancing their opportunities to participate and position themselves as actors in authentic scientific initiatives. The GreenComp framework defines sustainability as "prioritizing the needs of all life forms and of the planet by ensuring that human activity does not exceed planetary boundaries" and refers to sustainable development as processes to stimulate or achieve progress in sustainable ways (Bianchi et al., 2022). Henke & Elster (2022) introduce guiding principles to promote action competence in the context of education for sustainable development in schools, following a design-based research approach. Citizen participation in collecting environmental data is implemented in various ways. Helbig et al. (2021) provide a comprehensive overview of scientific projects that utilize wearable sensors, for example. From these approaches, we derive three guiding principles for a workshop design: contextual anchoring in everyday practices, shared control in design decisions, and materialized reflection through prototyping.

Method

The study follows a participatory design approach with children, drawing on cooperative inquiry and low-fidelity prototyping traditions (Druin, 1999, 2002). These approaches are particularly suited to exploring children's perspectives on technology and environmental phenomena, as they support expression beyond verbal articulation. Hagen et al. (2012) introduce a method matrix for designing with children and aligning them with specific activities in the design process, such as the "bags of stuff" method for low-tech prototyping. The bags of stuff represent a collection of materials, including paper, scissors, glue, markers, etc., used to create technology prototypes in response to specific questions, maintaining focus on the design task (Knudtzon et al., 2003). Based on these principles, a three-stage workshop was developed to elicit 10-14-year-old pupils' outdoor activity contexts, relevant environmental variables, and design ideas for environmental sensing artifacts.

Workshop Stage 1: The Context Of Outdoor Activities

The first stage of the workshop focuses on eliciting pupils' everyday outdoor activities and the contexts in which these activities take place. Using a structured template, participants describe their outdoor activities by outlining the activities themselves, required items, modes of mobility, and the social setting. This information provides insights into pupils' lived outdoor practices and the situational conditions under which environmental sensing could potentially be integrated. Pupils talk about their experiences and how they relate to their surroundings in the following phase. Based on their perceptions and observations, they identify specific environmental elements that caught their attention during these activities. To convey these observations, they employ evocative language. This step is intended to document their preliminary, experience-based comprehension of environmental conditions prior to delving into more formal methods of measurement. This initial phase lays the groundwork for later workshop sections by gathering qualitative data regarding the contexts of the pupils' activities and their sensory experiences.

Workshop Stage 2: Environmental Data And Measured Variables

The second stage of the workshop is all about linking what pupils notice in their environment to actual things that can be measured. Building on the sensory experiences from the first stage, pupils explore common environmental factors important in urban settings, such as temperature, noise, and air quality. In this part of the workshop, pupils acquire basic knowledge of the most common measured values and distinguish which can be experienced through their senses and which require a specific tool for detection. After this introduction, participants add measured variables to the ones they named earlier and generate a richer picture of possibilities for measuring relevant environmental data. To conclude this stage, participants reflect on possible effects caused by the identified environmental influences and formulate concrete ideas for reducing these effects.

Workshop Stage 3: Designing An Environmental Sensor For A Specific Context

In this stage, pupils design and create individual non-functional environmental sensor prototypes. The design of the artifacts is supposed to address the previously defined criteria of an outdoor activity and the identified environmental influences. Therefore, participants use dummies for electronic and sensor components, as shown in Figure 1. These components are intentionally aligned with real-world technical counterparts to introduce basic technical constraints without requiring functional implementation.

The prototyping process aims to support materialized reflection on how environmental data collection and feedback could be embedded in pupils' everyday outdoor practices. At the end of

the workshop, participants present their results, explain their design, and provide reasoning for their design decisions. This stage generates qualitative data on pupils' conceptualizations of environmental sensing and the role of material prototyping in linking everyday contexts with abstract measurement concepts.

Figure 1: 3D printed sensor dummies for technical components. (red = sensors, blue = microcontrollers and GPS module, yellow = output components, green = power supply).



Data Collection And Analysis

Data were collected through the templates participants used to describe their outdoor activities, note the environmental influences they experienced, document the actions they envisioned to mitigate negative effects, and through the resulting prototypes. The workshop's design stage was video-recorded. These records were used to analyse the design process the participants followed and the design decisions they made. This wide variety of collected data enabled data triangulation (Flick, 2011) to yield comprehensible insights into participants' conduct and resulting designs. Data were analysed thematically (Braun & Clarke, 2006), and the resulting themes are aligned with the stages of the workshop and the single tasks. The resulting prototypes, their functionality, and included measured variables were tracked back to the initial descriptions of outdoor activities, needed items, modes of transport, and relevant measured variables to identify how the results correspond with the initially described context and which new factors emerged during the design stage. The workshop design and its materials were discussed in semi-structured expert interviews (Meuser & Nagel, 1991), which included a teacher (IP1), a researcher in the field of learning technologies and eDidactics (IP2), and a researcher and teacher educator covering the fields of health and environmental education (IP3). The expert interviews were video recorded, transcribed, and analysed thematically.

Results

The results are based on data collected during three workshops with 57 participants across three different schools in Vienna, Austria. The participants are aged 10-14 years and have not received subject-specific computer science teaching. The analysis focuses on patterns across activity contexts, environmental perceptions, and design concepts.

Contexts of outdoor activities

Analysis of the activity descriptions revealed dominant themes in pupils' everyday outdoor practices. A large proportion of activities were related to sports and physically active leisure, including both organized sports and informal play. Swimming for leisure, ice skating, and various ball games were highly referenced by the participants. Other referenced activities reflect

participants' transitional and social activities, often including their friends and relatives, such as relaxing, going for a walk, sitting in the park, and shopping.

The referenced activities were associated with items participants regularly use during their outdoor activities. Various types of bags, backpacks, and other carrying aids were referenced, as well as drinking bottles and nutritional supplements. Leisure and sports equipment, such as balls, rackets, skates, specific clothing, and other sports gear, was assigned to the theme of physical activity. Money was highly referenced to be a relevant item for outdoor activities, as well as the (smart)phone for communicating with others. Skateparks, soccer goals, and other infrastructure were mentioned as relevant, as well as proper conditions such as nice weather. Regarding their mobility, participants identified walking, cycling, riding a scooter, being driven by car, and using public transportation as the most relevant options.

When asked about their perception through their physical senses, participants most frequently referenced their sports equipment and temperature in relation to their sense of touch. Regarding their sense of smell, nature was highly referenced, and for their auditory sense, they referenced various animals, people, and sports equipment, such as the sound of hitting a ball.

From Physical Senses To Measured Variables

In addition to phenomena participants perceived with their physical senses, they reflected on specific measured values relevant to their outdoor activity. Weather and air quality variables were identified, including temperature, wind speed, particulate matter, CO_2, and light intensity. Noise was mainly referenced as general noise, rather than noise from specific sources. In the theme of soil & water, soil moisture and water quality were referenced. Traffic-related references include vehicle count and vibrations caused by vehicles. Many references include values that do not address environmental measures in any sense, such as the velocity of a soccer ball or a bike ride, but are closely related to the outdoor activities of the participants.

Participants reflected on potential actions to improve the conditions of their outdoor activities. Requests for regulations include implementing threshold values for pollutants. Improvements of conditions require reducing noise and improving water quality. Regarding transport, having fewer cars and fewer cargo ships is desired. Ideas for enhancing public infrastructure include additional greenery and increased shading. Actions that describe individual behaviour address proper nutrition and hydration, as well as the use of earplugs to reduce noise exposure.

The second stage of the workshop demonstrates how environmental conditions can be measured using specific sensors and identifies the relevant measured variables. It clearly shows that, in addition to environmental measures, participants are highly interested in measures directly related to their outdoor activity, such as the speed of a soccer ball.

Context-Based Designs Of Environmental Sensing Devices

In the third stage of the workshop, participants were tasked with designing and creating a sensor prototype for an outdoor activity, working in groups of three to five pupils using the available materials and tools. This design and prototyping stage produced 24 non-functional prototypes for environmental sensors. Three distinct patterns were found, as illustrated in Figure 2.

The first design pattern features wearable sensors. Sensing technology is incorporated into clothing items such as hats, bracelets, and vests. These sensors continuously gather data on the wearer and provide quick feedback, linking their surroundings to their sensations. Another design pattern involves sensors embedded in activities. These sensors are incorporated into sports gear or equipment related to the activity, such as entertaining devices, bags, or training tools. This combines environmental data with activity information to illustrate how people move, their

performance levels, and their locations. The third pattern involves sensors in places or things around us. These are set up in parks, streets, or private gardens. They monitor the environment over time and are usually intended for group use rather than providing information to individuals. In every design, pupils typically combine information about the environment with their own activity. It appears that sensing the environment was more relevant in relation to people's preferences, daily activities, and social circles.

Figure 2: Examples of resulting designs: Cap with temperature sensor (wearable sensor), portable radio with temperature sensor (activity-related sensor), garden fairy lights (placed sensor).



Cross-Cutting Insights And Misalignments Across The Workshop Stage

During the three workshop stages, some recurring ideas and conflicts emerged. Many groups created sensor designs based on the activities and environmental factors they had previously identified. However, some groups started to focus more on activity or health information. In these cases, environmental sensing shifted to the background and became less closely tied to the original research. This difference highlights the conflict between allowing freedom in the design process and maintaining a strong focus on environmental sensing. The open prototyping phase encouraged creativity and engagement. However, sometimes pupils concentrated on aspects of their activities that were personally important to them rather than considering the environment in the first place. Nevertheless, these changes provide valuable insights into what motivates and interests pupils. The shift towards activity information suggests that environmental sensing is more meaningful to pupils when it relates to how they engage in activities, how they play, or what they care about. These results highlight the need for clearer transitions and reflection between workshop phases while allowing sufficient freedom. This would facilitate creative and relevant design processes.

Experts And Practitioners' Perspectives On The Workshop Design And Learning Potential

The results from the expert interviews reflect their perspectives on the *workshop setting*, its *materials*, the *resulting designs,* and *learning effects.* The experts emphasized the importance of seamless transitions between workshop stages, particularly when shifting from contextual analysis to prototype creation. They added that, without clear direction, pupils might lose focus on environmental issues and become more concerned with personal, activity-related actions. IP2 recommends using more structured templates to support transitions and maintain focus on the workshop goals. IP3 points out that gamification elements work well in this age group, and the templates could be designed like a gameboard where participants fill in information and develop ideas step by step. Regarding support, the experts noted that teachers should act as helpers, not co-designers, and that their role in the workshops should be clear. While some direction was considered beneficial for pupils' thinking and social needs, experts cautioned against teachers influencing pupils' design choices, as IP2 states: "They can supervise, and they can talk to children who are distracted doing other things and guide them back to the task, but not do the task for them. And you should try to write this down explicitly in your workshop setup." (IP2). The

experts also reviewed the workshop materials and noted that the information posters in the second part contained too much text for the targeted age group. IP3 suggests to "…simplify it. With more illustrations, I only keep the most necessary facts. […] I would insert legends." (IP3). Using more pictures and better-planned note-taking was suggested to help pupils engage with and understand the material more easily. At the same time, the use of non-working technical models was well received, as they facilitate thinking about real design without the need for functional parts, as IP1 emphasizes: "Even though they weren't real sensors, it still made it somehow realistic, or gave it a feeling of seriousness." IP1 addressed the learning effects and stated that: "I was just thinking about whether, for some children, this was perhaps the first time they had to deal with the fact that there are specific values for measurements. […] it was certainly an eye-opener for some people to learn that there are sensors for these different measured values and in which units they are measured." (IP1), but also mentioned "that for some people, this then also expired in their short-term memory" (IP1).

The feedback from experts shows that the workshop setting and its goals are well set for discussing environmental sensing and creating sensor designs in a participatory session. Additionally, the experts' perspectives reveal improvements in materials, transitions between stages, and the definition of the teachers' role.

Discussion

The findings in relation to the research questions are discussed in this section and are situated within the theoretical frameworks of context-based learning and participatory design.

Interpreted through the lens of Contextual Design (Beyer & Holtzblatt, 1997), the findings indicate that pupils conceptualize environmental sensing in close relation to their everyday contexts. Participants were not only able to name a wide range of outdoor activities, but also to identify relevant environmental factors and metrics. The environmental conditions became meaningful primarily when embedded in concrete activities such as sports, mobility, or social leisure, supporting the CD assumption that design is grounded in their lived contexts.

From a participatory design perspective, pupils' conceptualisations demonstrate how shared control shapes meaning-making processes. The workshops enabled pupils to express environmental sensing concepts through their own interests and experiences, positioning them as contributors throughout the design process. This aligns with Schuler and Namioka's (1993) understanding of participatory design processes as a partnership between designers and users.

Pupils' frequent integration of environmental and activity-related measurements can also be interpreted as participatory urbanism. Benavides Lahnstein et al. (2022) found that pupils positioned themselves as learners and actors engaged with environmental issues relevant to their immediate surroundings. Environmental sensing was therefore not viewed as a stand-alone data collection task, but rather as a means of understanding and potentially responding to environmental conditions in urban contexts.

Interesting in our research was that there were clear differences in the transition between the stages of the workshop: While stages one and two were well integrated in terms of content, the transfer of their findings to stage three was not always consistent. Several groups designed prototypes that were only partially based on the previously named activities or metrics. This suggests that additional structuring aids, such as connecting worksheets and templates, checklists, or a brief re-mapping of the previous stage, could strengthen the connection between the stages. Regarding RQ1, this indicates that the presented workshops support pupils in conceptualizing the relationship between outdoor activities and environmental conditions by facilitating structured reflection on this relationship through the workshop process and its materials. Nevertheless, there

is room for improvement regarding the transitions between stages. As well, the focus on creating environmental sensors must be maintained throughout the design phase.

In RQ2, we investigate how the relationship between outdoor activities and environmental sensing materializes in sensor designs. The non-functional prototypes demonstrate how the pupils' ideas about the relationship between outdoor activities and environmental sensing were realised through design. These artifacts serve as tangible examples of how pupils integrated environmental sensing into activity-specific contexts, rather than using it as a technical fix. This demonstrated that environmental measurements were considered important when they were directly related to pupils' daily activities.

The conversation now shifts to how pupils integrated environmental sensing ideas into their non-functional prototypes, building on these conceptualizations. The findings also highlight a fundamental conflict between developing contextually accurate and environmentally relevant sensing concepts and ensuring transparency in the participatory design process. While openness encouraged creative and varied designs, it also sometimes led to activity-related features taking precedence over environmental sensing. In a few instances, however, this focus on activities also resulted in hybrid designs that integrated activity-related and environmental measurements, demonstrating pupils' attempts to negotiate relevance within the design space.

From a participatory design perspective, this conflict reveals a key challenge: balancing personal preferences with broader societal concerns. According to the results, environmental relevance requires intentional support rather than assuming it will emerge naturally. This is consistent with Iivari et al.'s (2024) call for participatory design that addresses important issues. To facilitate design processes that reflect pupils' lived experiences and engage with relevant environmental issues, it is crucial to balance creative freedom with thematic alignment.

Limitations

Several limitations of this study need to be considered. The workshops took place in school settings with limited time and resources, and the sustainability of the learning outcomes was not systematically assessed. The results, therefore, capture their ideas and understandings at a specific moment rather than documenting lasting learning. Group dynamics, such as the presence of dominant individuals or unequal participation, may have influenced how environmental concepts were expressed in the prototypes' designs. Finally, the workshop used a predefined set of materials for non-functional prototyping. While this made the activity accessible for the age group, it may also have narrowed the range of possible designs. This reflects a common tension in participatory design: offering enough structure to support learners while allowing space for open-ended exploration.

Conclusion And Future Work

Climate change mitigation is a challenge that needs strong efforts from all parts of the global society. Education and awareness-raising on climate change and the reduction of pollutants are integrated into curricula to support children in identifying how they are affected within their cultural context. The introduced participatory workshop setting, along with its materials, enables participants to reflect on environmental conditions related to their outdoor activities by creating a context-specific environmental sensor. The resulting designs illustrate how children envision environmental sensor artifacts for their outdoor activities, and that certain combinations of measured variables, collecting data on environmental conditions and the activity itself, are a fruitful approach for supporting engagement and long-term use.

From a didactic perspective, two levels of impact can be distinguished: (1) research findings on the contextualization of environmental measurement in the everyday lives of young people, and (2) learning effects in terms of environmental awareness, interest in technology, and design competence. While methodological openness provides rich design ideas for research, a stronger connection to school subject contexts (e.g., physics, geography, biology) can be helpful for sustainable learning effects. The results suggest that measurable, sensory variables (temperature, noise level, wind) facilitate intuitive access, while more abstract variables (e.g., NO_x, ozone) require additional didactic preparation.

Overall, the study confirms the potential of participatory, context-based design workshops to promote both environmental education and technical design in lower secondary education. To optimize the workshops, it is particularly advisable to strengthen the common thread between stages in terms of content, make the materials more age-appropriate, and create opportunities for further in-depth work in the classroom. Additionally, in future work, the dummies representing technical components are to be replaced by functional parts, enabling children not only to design sensors but also to collect real-world data and draw conclusions about environmental conditions affecting their outdoor activities.

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Section: Sex Education, Equality, And Menstruation

ESERA 2025 Copenhagen

Learning About The Menstrual Cycle Through The Use Of Narratives In Initial Teacher Education

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Human biology and health education are extremely important topics in secondary school and, by extension, in teacher education. In particular, there are several misconceptions and reductionist ideas associated with teaching and learning about the menstrual cycle. Within this framework, we set out to develop a teaching sequence to foster a comprehensive understanding of the biological and functional concepts related to the menstrual cycle. The study used a design-based research approach. The activities were implemented in an initial teacher training course in Córdoba, Argentina, focusing on creating multiple narratives about the menstrual cycle and reflecting on the stories of different characters. The results show that the pre-service teachers constructed contextualised ideas about the menstrual cycle and that the pedagogical resources developed facilitated a practical visualisation of the theoretical content, promoting the expression and questioning of notions, taboos, emotions and experiences related to this process.

Keywords: Health Education, Teacher Education, Human Biology.

Introduction

In secondary schools in Córdoba (Argentina), the biology curriculum broadly covers Human Biology, including biological systems, organs and processes. However, much of this content is complex and abstract for students, which often leads to rote learning (Ariza & Navarro, 2021). In addition, many of these topics are closely linked to health education, which requires teaching oriented towards the analysis of information, the development of critical thinking skills, reflection, problem-solving and the ability to establish relationships (Jiménez-Aleixandre & Puig, 2022).

Regarding specifically the concept of the menstrual cycle, several authors highlight the variety of misconceptions and reductionist ideas linked to this process, including approaches that focus only on reproductive aspects, notions that emphasise the uniformity of bodies, and approaches that override emotions, experiences or cultural meanings about this process (Blázquez Rodríguez & Bolaños Gallardo, 2017; Kohen, 2018; Sirovina, 2022). This view makes it difficult for students to connect the menstrual cycle to their daily lives and understand its relevance to health and well-being. Droguett Muñoz and Camacho González (2021) assert that the teaching of the menstrual cycle reflects the shortcomings of the current education system, which is not adapted to students' needs. Learning about the menstrual cycle involves understanding complex biological processes that require in-depth preparation, making it a challenging subject. In this sense, it is necessary to improve teacher training in mastering these concepts so they can teach them more deeply, avoiding simplistic explanations.

The menstrual cycle is a multidimensional phenomenon in which biological, psychological, social and cultural aspects interact. This underlines the need to analyse the psychosocial aspects of the menstrual cycle, considering not only the biological functions but also the psychological, anthropological and cultural dimensions (Botello-Hermosa & Casado-Mejía, 2015). This integration requires rethinking the teaching of the menstrual cycle so that students not only

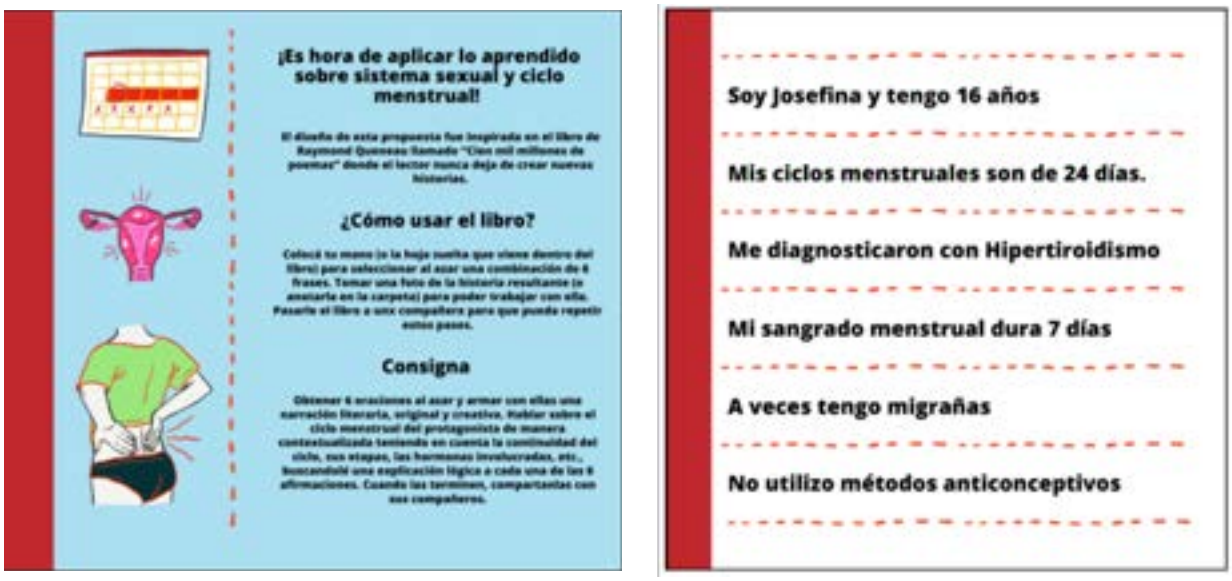
receive information but also understand its multidimensionality and apply it to specific contexts. In this sense, narratives offer the potential to convey the conceptual content of school science, contribute to meaningful understanding by relating central ideas in a plot, and positively impact student motivation, among other issues (Revel Chion & Adúriz-Bravo, 2022). This proposal seeks to stimulate student motivation and foster situated and contextualised understanding, recognising the diversity of emotions and bodies, each with unique personal experiences.

Method

The study was conducted within a design-based research approach, which aims to generate knowledge to improve teaching practices by preparing, implementing, and analysing didactic designs (Guisasola & Oliva, 2020). The didactic design aimed to promote a comprehensive understanding of the biological and functional concepts of the menstrual cycle from a holistic, multidimensional perspective. The theoretical goal was to produce evidence-based contributions to the teaching of human biology, specifically the menstrual cycle, through narratives. The proposal was carried out in collaboration with the professor responsible for the 'Human Biology' course in an initial teacher training program in Biology, with seven pre-service teachers participating in its implementation. The results were analysed qualitatively.

In this context, the didactic tool ‘One Hundred Billion Menstrual Cycles’ (Figure 1) was created (Manetti, 2023). This small book allows readers to create multiple narratives about the menstrual cycle, featuring different characters. This tool aims to promote a comprehensive understanding of the biological, social, and emotional aspects of this concept.

Figure 1. Two pages of the book designed for the development of the didactic sequence. The first page explains how to use this teaching tool. The second page represents an example of the six sentences that could be combined to create a narrative.



The first part of the intervention consisted of a theoretical introduction to the menstrual cycle, addressing its definition, duration and characteristics. The pedagogical approach prioritised critical dialogue in the classroom, supported by audiovisual tools and constant feedback. Then, the pre-service teachers created contextualised narratives with one of the book's characters as the protagonist. Finally, in a group dynamic, participants shared their stories, highlighted the common and unique points of the narratives and reflected on how to integrate this knowledge into their daily lives.

The narratives were collected to evaluate the teaching sequence and to assess the tools used. Each narrative was evaluated on four components: pragmatic, rhetorical, logical, and theoretical. Following Revel Chion et al. (2013), the pragmatic component refers to the appropriateness to

the context that gives meaning to the story, the rhetorical component implies the intention to persuade the reader or listener of the narrative, the logical component represents the complex syntactic structure of the text and the theoretical component alludes to the theoretical model of reference, in this case, the menstrual cycle.

To deepen the theoretical component, the categories of analysis proposed by Bahamonde and Gómez Galindo (2016) were restructured, and the ideas of continuity, interaction, transformation and integration present in the narratives were evaluated. The concept of continuity implies conceptualising the sexual system and folliculogenesis as the basis of the menstrual cycle. The notion of interaction emphasises that the menstrual cycle is not only dependent on the sexual system but also cuts across all systems of the organism. Transformation refers to the evolving nature of the follicle throughout the menstrual cycle. Integration involves understanding the connections between the sexual system, other bodily systems, and the emotional experiences that occur during the cycle, establishing a logical, biological and emotional explanation for the process.

Each category was assessed using a rubric developed by the researchers, with the following values assigned: excellent, satisfactory, needs improvement or insufficient. Additionally, two surveys were administered, one at the beginning and the other at the end of the development of the didactic sequence, to assess pre-service teachers' knowledge and opinions on the subject and the proposal developed.

Results

Most narratives demonstrated contextual appropriateness, structural coherence, and persuasive presentation. In terms of the theoretical component, the most prominent category was integration, with most narratives showing a clear understanding of the stages of the menstrual cycle, the hormones involved, the characteristics of different methods of contraception, and the development of a logical, biological and emotional explanation for the symptoms presented in the book (Table 1). Regarding the other three dimensions, while some narratives were auspicious, others showed insufficient development. The most challenging aspects in this regard were the following: 1) only three narratives presented the interaction between the ovarian cycle, the endometrial cycle and the hormones produced in the hypothalamus, and 2) the transformation of the follicle into an egg cell was not captured in the writings. However, during the oral exchange of the narratives, the participants demonstrated an understanding of these topics. This finding suggests that the narrative writing task could be enhanced to foster greater development in this area.

Table 1. Assessment of the theoretical component across the seven narratives, showing the distribution of qualitative ratings for continuity, interaction, transformation, and integration.

Narrative	Continuity	Interaction	Transformation	Integration
Narrative 1	Satisfactory	Needs improvement	Needs improvement	Insufficient
Narrative 2	Excellent	Needs improvement	Excellent	Excellent
Narrative 3	Needs improvement	Insufficient	Insufficient	Satisfactory
Narrative 4	Needs improvement	Excellent	Insufficient	Satisfactory
Narrative 5	Needs improvement	Excellent	Insufficient	Excellent
Narrative 6	Needs improvement	Excellent	Insufficient	Excellent
Narrative 7	Needs improvement	Insufficient	Excellent	Excellent

Beyond identifying biological elements, the analysis of the narratives revealed an integration of the menstrual cycle as a multidimensional phenomenon. Participants articulated biological processes in relation to emotional experiences, social contexts, and life trajectories of the characters they constructed. This integration was particularly evident in narratives that incorporated references to stress, identity, life stages, access to healthcare, and contraceptive decisions. Such narratives suggest that the use of contextualised storytelling facilitated a shift from a fragmented understanding of the menstrual cycle to a more situated conceptualisation.

An additional relevant outcome concerns the explicit emergence of emotions associated with the menstrual cycle. Many narratives incorporated emotional dimensions such as anxiety, relief, discomfort or ambivalence. These emotional references were not treated as mere anecdotes but were often linked to biological explanations or contextual factors, such as hormonal fluctuations, social expectations, or stressful life situations. This finding suggests that narrative-based activities may create pedagogical spaces that legitimise emotional expression and contribute to questioning socially rooted taboos surrounding menstruation.

The diversity of characters represented in the narratives constitutes another significant result. Participants constructed stories that represented individuals at different life stages and with diverse bodily and identity-related experiences, as well as individuals with irregular cycles, health conditions, or diverse reproductive choices. This diversity allowed pre-service teachers to problematise the idea of a "standard" menstrual cycle and to recognise variability as a central feature rather than an exception. In this sense, the narratives functioned as a didactic resource to challenge universalised and normative models commonly found in school biology teaching.

Regarding the surveys, most participants highlighted the usefulness of the book and the infographic for understanding the menstrual cycle. The pre-service teachers highlighted that the book "One Hundred Billion Menstrual Cycles" enables them to combine sentences to create stories, engaging in a creative and reflective exercise while applying theoretical concepts in a practical context. In addition, the comprehensive, contextualised and holistic approach enabled participants to incorporate social, cultural and emotional aspects into their narratives, enriching their understanding of the menstrual cycle as a complex and multidimensional phenomenon.

Conclusions

The results indicate that the activities proposed during the sequence, including the use of the book 'One Hundred Billion Menstrual Cycles', enriched the understanding of the menstrual cycle, providing a more comprehensive and contextualised perspective. These pedagogical resources facilitated a practical visualisation of the theoretical content, promoting the expression and questioning of notions, taboos, emotions and experiences related to the menstrual cycle and menstruating bodies. Thus, a multidimensional construction of the cycle has been promoted, encompassing physiological, social, emotional, cultural, economic and health aspects.

Besides, it is important to highlight that the book 'One Hundred Billion Menstrual Cycles' offers opportunities to explore various topics, such as sexual diversity, pregnancy, and endocrine disruptors, among others, issues that we will be able to address in new implementation cycles of our proposal within the framework of the design-based research approach.

Although the results were positive, opportunities for improvement were identified. It is suggested that the narrative task be reformulated to deepen the teacher's theoretical knowledge, thereby leading to more enriched stories. It is also proposed to include more pages in the book, as the first sentences were less frequently chosen by participants, leading to the same characters and stories being selected by different pre-service teachers. This modification aims to generate a greater variety of stories and avoid repetition of the same characters. In dialogue with the professor who

carried out the sequence, we assert that it is essential to implement the strategy across various institutions to evaluate its effectiveness in different contexts and educational levels, in order to adjust the proposal and apply it transversally throughout the education system.

Despite the promising results, this study is limited by the small number of participants and its implementation within a single institutional context. Future research could explore the use of this narrative-based approach in other teacher education settings and educational levels. Additionally, further studies could investigate how narrative work interacts with other scientific practices, such as modelling or argumentation, in the teaching of human biology.

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Exploring Adolescent Student's Knowledge and Beliefs about Menstruation and Understanding the Influence of Education on It.

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This study explores the knowledge, beliefs, and attitudes regarding menstruation among middle school students in an urban co-educational school in India. The research investigates how formal education influences students' understanding of menstruation, with a focus on dispelling myths and misconceptions. Data was collected through a survey administered to 62 students from Grades 7 and 8, with a focus on comfort levels, scientific knowledge, misconceptions, and information sources. Findings indicate that while Grade 8 students demonstrated improved awareness of menstruation compared to Grade 7 students, significant gaps remain in scientific understanding and there are persistent cultural misconceptions. Boys exhibited lower levels of knowledge, they also showed a higher tendency to believe in menstrual myths. Girls, in contrast, had better knowledge. The study underscores the importance of integrating boys into menstrual education to reduce stigma and promote gender inclusivity. It suggests that menstrual education should begin before Grade 7 to ensure accurate information is provided before misconceptions take hold. It also calls for teacher training and more open discussions in schools. The research highlights the critical role of health education in challenging menstrual taboos, improving understanding, and fostering empathy across genders, leading to a more inclusive and supportive school environment.

Key words: Health Education, science education, cultural context

Introduction

Menstruation remains a critical area of research, particularly in understanding how education shapes students' knowledge, beliefs, and attitudes. The stigma and misconceptions surrounding menstruation often create barriers to open discussions, reinforcing restrictive social norms. In India, menstruation is frequently associated with cultural taboos that portray it as impure, limiting the participation of menstruating individuals in religious and social activities. While education and media exposure have contributed to changing perceptions, misinformation persists, affecting adolescents' understanding and menstrual health practices. This study explores how middle school students in an urban co-educational school in India understand menstruation and examines whether formal education helps dispel myths and misconceptions.

This study is grounded in Social Constructivism Theory, emphasizing that knowledge is shaped through social interactions, cultural norms, and education. Vygotsky's perspective highlights how family, peers, media, and school influence students' perceptions of menstruation (Akpan et al., 2020). Findings inform curriculum development, teacher training, and gender-inclusive education to challenge misconceptions and foster awareness.

Related literature

Research highlights persistent gaps in menstrual awareness among adolescents. A UNICEF (WaterAid, 2018) study found that 52% of girls in India are unaware of menstruation before menarche, leading to confusion and anxiety. Lack of education contributes to school absenteeism, with 23% of girls dropping out due to stigma and inadequate support (Garg & Anand, 2015). A

review of menstrual health programs in India found that schools with structured education initiatives had lower absenteeism, particularly in model schools with NGO support (Sivakami et al., 2018). In 2014, the Ministry of Health and Family Welfare introduced the National Adolescent Health Programme, called Rashtriya Kishore Swasthya Karyakram (RKSK). This initiative outlined specific guidelines aimed at promoting education, awareness, and improved menstrual hygiene management (MHM) through a peer education approach. The program focused on strengthening protective factors among adolescents to foster resilience, using both community-level and school-based strategies. Although this program aims to address an important issue, we did not find any literature on the actual implementation strategies or on the effectiveness of this programme.

Global research reinforces these findings. In Uganda, students' menstrual knowledge significantly improved after targeted educational interventions, demonstrating the value of structured school-based programs (Kansiime et al., 2020). Studies from Ghana and Afghanistan emphasize the role of sociocultural norms in shaping menstrual beliefs and the importance of including boys in menstrual education to foster a more inclusive learning environment (Mohammed & Larsen-Reindorf, 2020). In India, a cross-sectional study revealed that 76.2% of schoolgirls believed menstruation involved the removal of impure blood, highlighting widespread misconceptions (Seenivasan et al., 2016).

Despite menstruation being part of school curricula, many teachers feel unprepared or uncomfortable discussing the topic (Mukerjee et al., 2023). The success of model schools, which integrate NGO-supported menstrual awareness programs, suggests that structured interventions significantly improve students' understanding and experiences.

Research Questions

This study examines the following:

1. What are the knowledge, beliefs, and attitudes regarding menstruation among 7th and 8th-grade students?
2. What are the sources of this knowledge?
3. How does menstrual knowledge differ between Grade 7 (before formal instruction) and Grade 8 (after formal instruction)?
4. Are there gender-based differences in menstrual knowledge and beliefs?

Research Methodology

This study employed a survey method to examine students' knowledge and beliefs about menstruation. Consent was obtained from the head teacher, and a paper-pencil questionnaire was administered separately to Grade 7 and Grade 8 students. The questionnaire included basic demographic questions followed by 15 menstruation-related questions—one open-ended and 14 multiple-choice or checkbox-based, 3 of these questions were based on the questions used by previous researchers, such as Sakhi et al. (2023). Data was anonymized and analysed using descriptive and inferential statistics.

Study Setting, Participants, And Instructional Context

The study involved 28 Grade 7 students (17 males and 11 females) and 34 Grade 8 students (23 males and 11 females) from a government school in a metropolitan city in India. The school serves underprivileged students, many from migrant families with low parental education. The average age of participants was 12 years (Grade 7) and 13.25 years (Grade 8).

Menstruation-related content at the study site was taught by a female teacher, 48 years old with 11 years of teaching experience. Instruction framed menstruation as a health and rights topic relevant to students of all genders, and the teacher reported encouraging early, curriculum-integrated coverage (e.g., from Grade 5) given earlier pubertal onset and students' exposure to potentially unreliable online information. The topic was introduced through lessons on puberty and adolescence (physical changes, diet/nutrition) and then extended to reproductive development and the menstrual process. Teaching was interactive and used government-authorized materials (e.g., NCERT/SCERT videos), QR-code-linked textbook resources, and project-based student presentations. In the co-ed classroom, the teacher anticipated discomfort (particularly among boys) and addressed it through explicit scientific explanation and structured discussion intended to normalize the topic and support respectful participation.

Findings

This section presents students' knowledge, beliefs, and attitudes regarding menstruation, followed by grade-wise and gender-based differences. The findings are structured around four key themes: comfort level, scientific knowledge, misconceptions and superstitions, and sources of information.

Students' Knowledge, Beliefs And Attitude Regarding Menstruation

Questions Related To Comfort Level

When asked "Do you know about menstruation?", 36% of Grade 7 and 76% of Grade 8 students responded 'Yes', suggesting increased awareness with age and curriculum exposure. 50% of Grade 7 and 15% of Grade 8 said 'A little bit'. 14% of Grade 7 and 9% of Grade 8 students did not know the term.

For "Do you feel embarrassed discussing menstruation?" 25% of Grade 7 and 9% of Grade 8 students said 'Yes', while 50% of Grade 7 and 26% of Grade 8 said 'Sometimes'. 21% of Grade 7 and 62% of Grade 8 students did not feel embarrassed, indicating, although most students did feel embarrassed, there is a decline in stigma with increased age and curricular exposure.

Questions Related To Scientific Knowledge

For "At what age do girls typically start menstruating?", 68% of Grade 7 and 88% of Grade 8 students correctly answered '10-16 years'. The remaining students either underestimated (6-9 years) or overestimated (16-20 years) the age.

For "At what age do women stop menstruating?", 39% of Grade 7 and 59% of Grade 8 students correctly answered '45-55 years', showing lower awareness than that of age of menarche, while the remaining underestimated (30-45 years) or overestimated (after 55 years) menopause age.

Responses for "Which hygiene products have you heard of?" are summarized in Table 1.

Sanitary pads were the most well-known product, likely due to advertisements and availability in general stores. Despite being eco-friendly and traditional, cloth napkins and folded cloth were less recognized.

For an open ended descriptive question, in Grade 7, 4% identified menstruation as a reproductive process, 11% as a periodic process, and 75% lacked scientific understanding. 11% mentioned superstitions such as *"women would be dirty"and "women shouldn't be touched"*.

In Grade 8, 26% identified menstruation as reproductive, 24% recognized it as periodic and 15% mentioned hormones. However, 53% did not understand the shedding of the uterine lining, and 47% lacked knowledge about its periodic nature, indicating gaps despite curriculum exposure.

Table 1: Percentage of students who knew about each of the different hygiene products.

	Sanitary pads	**Folded piece of cloth**	**Menstrual cup**	**Tampons**	**Others**	**Cloth napkin**
Grade 7	96%	11%	14%	11%	0%	0%
Grade 8	68%	15%	12%	15%	21%	9%
Combined	81%	13%	13%	13%	11%	5%

Misconceptions And Superstitions

Students reported commonly held beliefs about menstrual, including:

"Girls cannot go out during menstruation."

"Menstruation should be kept secret."

"Menstrual blood is impure."

In response to "Have you heard of any of the following superstitions?", results are given in Table 2.

Table 2: Percentage of students who are aware of different superstitions.

Superstition	**Grade 7**	**Grade 8**	**Combined**
Menstruating girls should not enter temples or religious places	82%	71%	76%
Menstruating girls should avoid physical activities	43%	47%	45%
Menstruating women and girls should not cook or touch certain food items	39%	47%	44%
Menstruating women and girls should sit separately	36%	44%	40%
Menstrual blood is impure	32%	41%	37%
Menstruation should be kept a secret	36%	35%	35%
We should not touch menstruating women and girls	21%	18%	19%

The belief that menstruating girls should not enter religious places was most widespread. Percentages were similar across grades, suggesting deep-rooted cultural influences.

For "Should dietary restrictions be followed during menstruation?", 46% of Grade 7 and 35% of Grade 8 students said 'Yes', while 43% of Grade 7 and 50% of Grade 8 were unsure.

For "Should girls/women attend school or work during menstruation?", responses were:

25% of Grade 7 and 18% of Grade 8 said 'Yes'.

46% of Grade 7 and 65% of Grade 8 said 'Only if physically fit'

21% of Grade 7 and 15% of Grade 8 said 'No'.

For “Should girls/women participate in physical activities during menstruation?” 36% of Grade 7 and 29% of Grade 8 responded affirmatively, while 44% of Grade 8 said ‘No’, reflecting strong beliefs in activity restrictions.

Differences Between Grade 7 And Grade 8 Students

In addition to qualitative analysis, we also calculated the total scores based on the questions related to knowledge about menstruation. Average score of Grade 8 students (M=63.89%, SD=18.3) was significantly higher than that of Grade 7 students (M=52.98%, SD=21.2) with a moderate effect size ($t(60) = 2.17$, $p = .03$, $d = 0.56$). This indicates that the inclusion of the topic in the textbook and the classroom instruction must have played some role in this improvement.

Table 3: Sources of information about menstruation according to their percentages.

Source	Grade 7	Grade 8	Combined
Teacher	21%	59%	42%
Textbook	4%	62%	35%
Mother	50%	15%	31%
Friends	29%	26%	27%
T.V. advertisement	32%	24%	27%
Internet	39%	9%	23%
A doctor or a health professional	7%	12%	10%
Someone else in the family (sister / grandmother / father etc.) Please specify	11%	3%	6%
Other books (If yes, name the books)	4%	3%	3%
Other sources. Please specify	0%	6%	3%

Sources Of Information

Students’ responses to the question “Where did you get information about menstruation? Tick on all that applies” are given in Table 3.

Teachers and textbooks were the most cited sources for Grade 8, while mothers, TV, and the internet were more common for Grade 7. Few students consulted doctors or health professionals.

For “Would you like to learn more about menstruation?”, 68% of Grade 7 and 59% of Grade 8 said ‘Yes’, while 38% of Grade 8 were uninterested.

For “Should schools play a larger role in menstrual education?”, 54% of Grade 7 and 62% of Grade 8 agreed, though 21% of Grade 8 students opposed it.

For “How would you prefer to learn?” students preferred health professionals (32%), books (29%), and videos (14%), which again suggests unwillingness to discuss the topic in public.

Differences Between Male And Female Students

Table 4 describes the gender-based differences (RQ4).

Table 4: Comparison of Male and Female Students' Knowledge of Menstruation

Category	Girls (%)	Boys (%)
Average Score	71.5% (SD = 15.0)*	52.1% (SD = 19.6)
Awareness of Menstruation	83%	43%
Correct Age of Menstruation	66.7%	33.3%
Correct Age of Menopause	61.1%	44.4%
Primary Source of Information	Mother (55%)	Internet (27%), Friends (28%)
Textbooks as a Source	23%	43%
Teacher as a Source	41%	43%
Friends as a Source	27%	28%
Doctors/Health Professionals	14%	8%
TV Advertisements	23%	30%
Correct Scientific Explanation	10-15%	10-15%
Belief in Myths	1%	25%
No Response on Scientific Info	8%	43%
Alternative Misconceptions	-	"Hormonal imbalance," "Puberty is menstruation"
Embarrassment in Discussing Menstruation	14%	18%
Belief in Dietary Restrictions	50%	35%

* An independent sample t-test revealed that the average score of girls (combining Grades 7 and 8) was significantly higher than that of boys ($t(60) = 4.36$, $p < 0.00$).

Conclusions

The findings indicate a significant improvement in students' understanding of and beliefs about menstruation following formal instruction in Grade 8, compared to Grade 7 students who had not yet covered the topic of reproduction. However, while students demonstrate a foundational awareness, significant lacunae remain in their scientific understanding of the menstrual cycle. Consequently, even after formal instruction, menstrual myths and misconceptions remain prevalent.

A pronounced gender gap was also evident; male students demonstrated significantly lower levels of awareness and understanding compared to their female peers. While female students provided more accurate and informed responses, both genders remained influenced by social taboos and expressed feelings of embarrassment, often subscribing to entrenched myths and superstitions. Although both boys and girls relied on informal sources of information such as mothers for girls

and internet and friends for boys, textbooks and teachers remain a prominent source of information for both genders.

Recommendations

This study demonstrates the necessity for early and comprehensive menstrual health education (MHE). Within the diverse educational landscape of India, levels of menstrual literacy vary significantly across cultural, social, and geographical contexts. Although schools have integrated menstruation into the curriculum, the effectiveness of its implementation remains inconsistent.

Current pedagogical approaches focus predominantly on physiological aspects, often neglecting the psychological and emotional dimensions of the topic. Therefore, a more holistic approach is required to foster a nuanced understanding among students. To enhance menstrual education in Indian government schools, there is a critical need for a curriculum that integrates biological facts with emotional well-being and gender sensitivity.

The study also indicates that textbook-based instruction is insufficient to dismantle long-standing misconceptions and deep-seated social attitudes. To address this, educational stakeholders must prioritize robust teacher-training programs and school-based interventions aimed at promoting menstrual health and hygiene (MHH). Such interventions are particularly vital in schools serving lower socio-economic strata, where misinformation and superstitious beliefs are often more entrenched due to limited educational access.

Furthermore, collaboration between schools, parents, and healthcare professionals is essential to ensure that education is both scientifically accurate and culturally sensitive. Normalizing discussions around menstruation is a prerequisite for fostering an inclusive environment that empowers students to challenge misinformation and advance gender equality.

Directions For Future Research

This study opens several avenues for future inquiry within science and health education. Future research should explore the long-term impact of early-grade menstrual education in mitigating social stigma and taboos. Longitudinal studies, in particular, would be valuable in tracking how students' understanding evolves over time and how formal instruction shapes their long-term perceptions and practices.

Additionally, comparative studies across diverse school settings—including rural, tribal, and private institutions—would provide deeper insight into how socio-economic and cultural variables influence menstrual literacy. Finally, there is a significant gap in literature regarding male students' perceptions of menstruation. Future research should focus on inclusive educational models that involve boys, as gender-segregated approaches often inadvertently perpetuate the very stigma and misconceptions that education seeks to eliminate.

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Section: Health Conceptions In Social Media

ESERA 2025 Copenhagen

Exploring Expert Conceptualizations Of Type-2 Diabetes Through Network Analysis: A Pilot Study

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This pilot study explores the conceptual structures of expert knowledge on Type-2 Diabetes (T2D) by applying network analysis to natural language explanations. Ten expert sources including interviews, educational videos, and a reference textbook, were transcribed and transformed into conceptual graphs through an automated pipeline that identifies [concept–relation–concept] triples from sentences. Concepts were categorized into domains of a T2D explanation, and semantic relations were encoded as directed edges. Network analysis techniques, amongst others betweenness centrality and backbone filtering, revealed both consensus and diversity in expert representations. While causes like obesity and family history were widely shared across the sources, treatment strategies lacked convergence. Individual graphs showed variation in node density, thematic foci, and conceptual connectivity. This study demonstrates a novel methodological pipeline for converting unstructured spoken or written expert discourse into analysable knowledge networks. It also suggests that conceptual divergence, even among experts, may influence how T2D is communicated and taught. This approach may extend to other disciplines where understanding conceptualization is crucial for a larger range of applications.

Keywords: Medical Science Education; Conceptualizations; Network Analysis

Introduction

Type-2 Diabetes

Organisms are in constant need for energy to sustain basic functions that include muscle contraction and cell division; for humans, a main source of energy is supplied via ingested food, notably from the glucose contained in carbohydrates. Insulin is a hormone that promotes the absorption of glucose in the blood by the cells of the body, amongst others in the liver and muscles. The latter organs convert the glucose into glycogen or triglycerides, which are forms of energy storage for the body to use. In the pancreas, beta cells are sensitive to the levels of glucose in the blood and promote (to decrease) or inhibit (to increase) insulin production to regulate the blood sugar. Type-2 Diabetes (hereafter T2D) is a chronic disease characterized by the inability of the body to either use insulin properly, or to produce enough of it, leading to high blood sugar levels. People affected by T2D may require regular external doses of insulin, for instance through injection shots, to avoid hyperglycaemic events that can cause potentially serious health complications.

While the pathogenesis of T2D is not fully understood yet, the disease is accepted as a complex multifactorial condition that is influenced by a combination of genetic, metabolic and environmental factors (Goyal et al., 2020). With a doubling of the number of people affected by T2D worldwide over 30 years, from 7% (1990) to 14% (2020) of the population, the condition is linked to over 1 million deaths per year on the planet, making it the 9th leading cause of mortality worldwide (Abdul Basith Khan et al., 2020). Because of the fast spread of the condition to all kinds of populations, T2D research is under important stress to tackle various associated challenges for public and global healthcare. Significant variability still exists in expert conceptualizations of T2D development, consequences, and subsequent medical care (Chatterjee

et al., 2017; Haddad & Haddad, 2018; Nauck et al., 2021). It is therefore critical to establish where the consensus lies with regards to T2D causes, treatment, and prevention.

Medical Science Education

Medical science education responds to the needs to keep the teaching and learning of medical science grounded in the fundamental sciences that compose it, as well as in research-informed best practices (IAMSE, 2026). As such, it has become increasingly multidisciplinary and collaborative, fuelled by an access to digital technologies and greater communication tools, but also because of a need to address rapidly developing complex healthcare challenges (Patel et al., 2005). This context has led to a growing pressure on medical science education to foster better medical reasoning reflected in decision making (Bornstein & Emler, 2001) and problem solving (Groen & Patel, 1985), as well as in the ability to conceptualize the disciplinary fields structuring the medical sciences (Shin, 2019). As academic instruction is provided to students by medical experts with different research profiles, their conceptualizations can influence their teaching contents and methods.

This study investigating the case of T2D within the medical sciences therefore asks the following research question:

What are the common points and differences between expert conceptualizations of T2D?

Revealing and analysing the different modes of knowledge structure and conceptual understanding amongst T2D experts (and, by extension, instructors) could inform teaching and learning in T2D education.

Methodological Frameworks

Conceptualizations And Expertise

Different propositions stemming from the epistemology of science and cognitive sciences have debated how to characterize conceptualizations — also referred to as conceptual understanding — knowledge structures and means to distinguish expertise from less mature stages of experience in a discipline. Amongst these theoretical frameworks, conceptualizations are described as the combination of *content knowledge* and the appropriate judgement on how to *structure* it (Farrington-Darby & Wilson, 2006); the accurate [explanatory/logical/probabilistic] *relations* between *elements in a body of information* (Kvanvig, 2003); the grasp of '*together-hanging*' of *elements in a body of mutually supportive cognitive commitments* (Elgin, 2012); or the patterns of *relations* between *scientific concepts* (Goldwater & Schalk, 2016). A broader discussion on the common points and differences between these propositions is presented by Weihs (2026). All these representations however share a same dual nature, assimilating conceptualization to a set of concepts and the structure that connects them together. Through this lens, expertise is the mode of conceptualization reflected by disciplinary experts, amongst others in their explanation of a topic. Prior research has shown that expert explanations are denser, invoking a higher number of concepts and more relationships between them (Chi et al., 1981).

Network Analysis

The presented dual nature describing conceptualization motivates the use of network analysis as an analytical framework, supported by the suggestion by Siew (2020) that networks can be a plausible representation of knowledge structures. Stemming from mathematical graph theory and applying its algorithmic power in various domains, network analysis characterizes the properties of graph objects, composed of elements/nodes and the relationships/edges between them. Network analysis has recently shown great potential in educational research, revealing relationships between actors, institutions, or concepts in educational contexts, in ways that were

not visible before (Koponen & Mäntylä, 2020). Similarly, network analysis has been successful in studying concept maps used in both teaching and learning settings (de Ries et al., 2022; Kapuza et al., 2020), and recently to investigate scientific explanations (Koponen & Huttunen, 2013; Wagner & Priemer, 2023; Weihs et al., 2025). Particularly, Weihs et al. (2025) developed a methodology to represent and analyse conceptual understanding and knowledge using network analysis, for conceptualizations prompted via scientific explanations contained in concept maps drawn by study participants. In order to operationalize this methodology, one therefore has to have access to conceptual networks capturing the semantics and logics of a scientific explanation; either by collecting concept maps, or by transforming textual explanations into conceptual networks.

Research Design

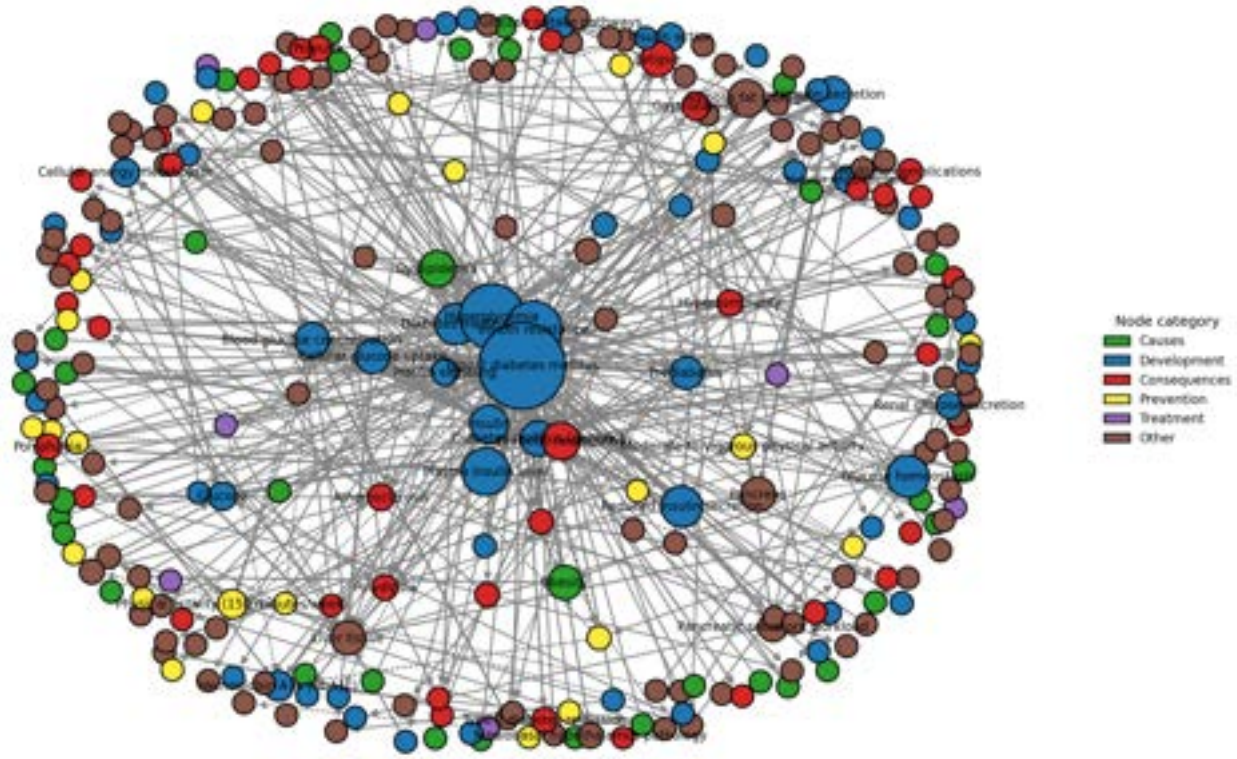
In this study, conceptual networks are created from 10 expert sources on T2D chosen as a convenient sample for their common English language, free accessibility online, and recency: five interviews publicly available on YouTube with the T2D experts Matt Barton from Griffith University, Sarah Hallberg from Indiana University, Vassiliki Bravis from Imperial College Healthcare, Lisa Knust from Riverside Eagle Harbor Primary Care, and Erik Richardson from Ridgeview Family Health; four YouTube educational videos on the topic of T2D by the science education channel *SciShow*, the medical education channel *Understand*, and the diabetes education channels *Animated Diabetes Patient* and *Diabetes UK*; and an excerpt of the fifth chapter 'Epidemiology of Type 2 Diabetes' from a reference textbook on T2D titled 'Textbook of Diabetes' (Holt & Flyvbjerg, 2024). To do so, the nine video sources from YouTube were downloaded as audio files with a script using the *yt-dlp* library, and transcribed with a script using the *whisper* library. Through a Python-coded automated routine using natural language processing tools, the transcripts were then split into individual sentences, and in each sentence, statements with the canonical logic of *[concept A–relation–concept B]* triples were identified. Both concepts in each statement, as well as the relation between them, were coded using inductive thematic analysis (Clarke & Braun, 2017), which informed the creation of an iterative codebook. Each concept was then attributed only one of the six used categories: *Causes*, *Development*, *Consequences*, *Prevention*, *Treatment*, or *Other*. Positive relations such as '*increases*' or '*leads to*' were weighted as 1, while negative relations such as '*decreases*' or '*prevents*' were weighted as -1. For each source, the thematically coded statements were then encoded as nodes connected by a directed edge using the *networkx* library, creating conceptual graph structures for every expert source. These networks were then explored using some tools of network analysis.

Results and Discussions

Joint 'Map Of Type-2 Diabetes'

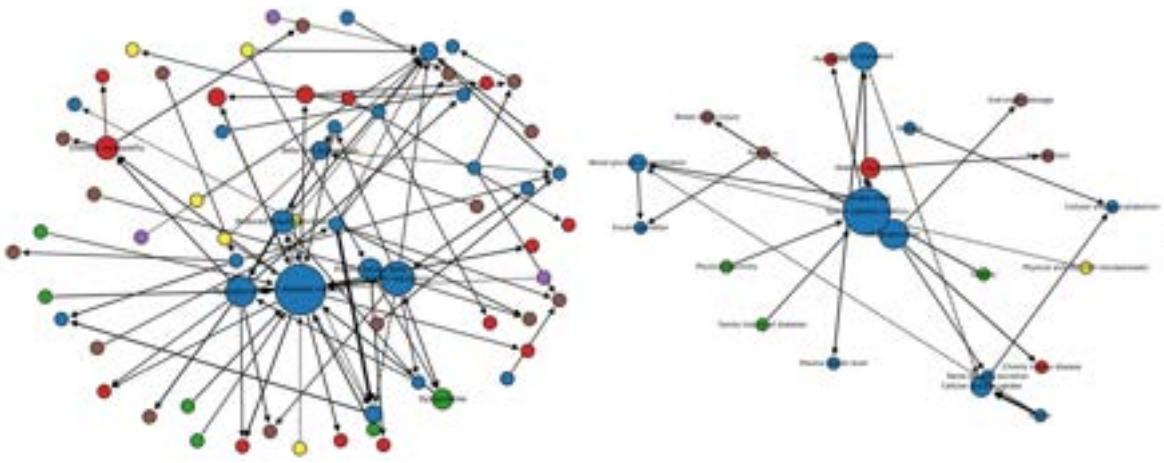
Compiling the information from the networks of all sources yields Figure 1. This joint network presents dense data that can however be regarded as the 'state of current knowledge' about T2D, according to the collected sources. It only shows the labels of the nodes with highest betweenness centrality, in other terms, the nodes most traversed by the paths between any two nodes of the graph network, which can be understood as the most essential concepts that connect the entirety of the knowledge contained in the structure. To improve readability, backbone graphs are created and presented in Figure 2.

Figure 3. Joint network aggregated from all 10 sources. The nodes are colored by category, the node size reflects their betweenness centrality, and the edge style encodes their sign (solid = positive, dotted = negative) with thickness proportional to their number of occurrences across all the sources.



The graph on the left in Figure 2 presents a weight-driven backbone network in which only edges repeated at least twice, even potentially by a same source, are chosen as a filtering criterion. In the right-hand graph, a consensus on edges mentioned by at least three sources is chosen as the filtering criterion. In the latter, three causes of T2D stand out: *obesity*, a *family history of diabetes*, and *physical inactivity*. Similarly, the consensual health consequences are *chronic kidney disease*, *diabetic neuropathy*, and *polydipsia* [an abnormally great thirst]. Such convergences in consensus answer the first part of this study's research question on the common points amongst expert conceptualizations of T2D. The only retained prevention method is *150min/week of physical activity*, and no treatment finds consensus on this graph. This could be due to the different foci of each source on the topic of T2D, which is explored in Figure 3.

Figure 2. Backbone networks filtering the joint network from Figure 1. The graphs are networks only displaying edges mentioned at least twice on the joint network (left), or mentioned at least by three sources (right). The encoding is the same as in Figure 1.



Individual Networks

Figure 3 presents the networks of each source separately. Amongst all sources, the textbook excerpt (bottom-right) particularly stands out, due both to its density in nodes and edges and to the variety of categories addressed. By contrast, some sources in the expert and YouTube channel groups focus significantly more on the prevention of the condition (in yellow), while other sources in both groups elaborate more on the consequences of the condition (in red). Likewise, certain sources present very coherent networks where almost all the nodes are interconnected, while others present two or more disjoint subgraphs, revealing a fragmented explanation where the transition from a topic to another could have been made more explicit. By comparing each individual network to the joint graph, it becomes possible to investigate which concepts and relations are unique to each source, as presented in Figure 4.

Figure 3. Individual networks for each source. The top panel presents the five expert sources (annotated with *E*), the bottom panel presents the four YouTube channel sources (*C*) and the textbook excerpt (*T*). The encoding is the same as in Figure 1.

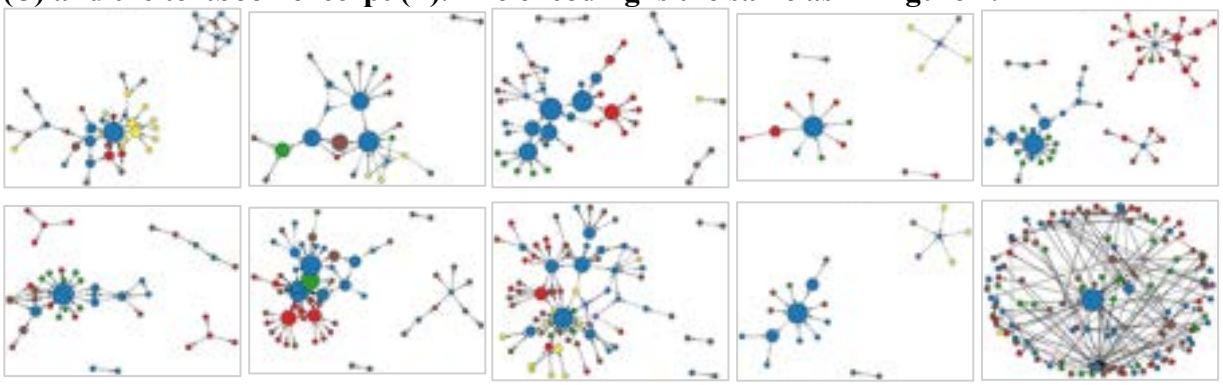


Figure 4. Uniqueness networks filtering the individual networks from Figure 3. The encoding is the same as in Figure 1; the order and annotations the same as in Figure 3.

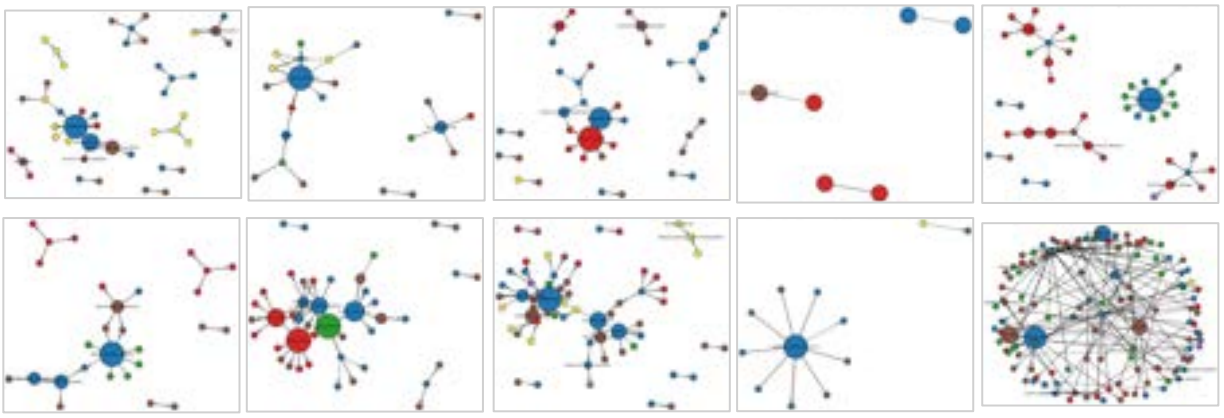


Figure 4 displays the nodes and edges that are specific to each source, and thereby shows what differences exist amongst them, answering this second part of this study's research question on the differences between expert conceptualizations of T2D. The expert source with highest focus on prevention (top-left) mentioned several unique concepts such as *dietary and physical activity monitoring*, *reduced fat, carbohydrate, and sugar intakes*, as well as *stairs climbing* and *more sustained housework and gardening activities* as overall *lifestyle modifications*. Sources focused on the causes (top-right and bottom-left) singularly mentioned *genetic predispositions and membership to high-risk ethnic groups*, but also *abdominal obesity*, *short sleep duration*, *smoking tobacco use* and *older age*, or even possible *medical therapy procedures* as factors elevating the risk of contracting T2D. Interestingly also, treatments are only mentioned exclusively across three sources, which, combined with an absence of consensus for the same category in Figure 2,

indicates possible ongoing debates in the T2D community about the remediation and interventions to cure the disease.

Conclusion

Preliminary Findings

This pilot study has investigated the conceptualizations of 10 expert sources on the topic of T2D, and shown that using automated coding routines enables to convert video into audio, then text, and finally into graph network data. This data can then be explored using network analysis tools, offering a new perspective on the knowledge structures and patterns of conceptual understanding of each source about their discussed topic. Common points as well as differences between sources were identified and helped supporting the idea that currently, there might only exist a partial consensus on the causes, consequences, development, prevention and treatment of T2D. At a time where the disease has become critical for public healthcare worldwide, more research building up on this pilot study could contribute to inform how to best teach the current and next generation of practitioners to most effectively address the global medical challenges associated with T2D.

Limitations

Despite its exploratory nature, this pilot study is subject to several limitations reducing its current scope and explanatory power. First, the small sample situates any claim outside of the realm of statistical significance, rendering the discussions mostly about first order patterns and tendencies. Then, only a triangulation of the used sources with commentary from other T2D experts — or another kind of admitted 'disciplinary truth' — about the results could help validate the findings and ensure that the discussion is grounded in contemporary T2D research, notably by confirming or rejecting statements from the sources. Also, as thematic analysis typically requires measuring an intercoder accuracy score, the analysis performed in this study has not been rigorously verified on a large enough sample to guarantee a maximal level of reliability. Finally, this study assumed that conceptualizations affect how experts teach when becoming educators but did not empirically address how these findings might impact educator training, teaching practices, or learning techniques. These important considerations are left open for follow-up work on the topic.

Implications

Beyond the complementary perspective that this pilot study presents on T2D conceptualization, the methodology it developed and used to convert natural spoken and written language in conceptual networks that capture the semantics and logics of a scientific explanation could have a larger impact on many other types of research. In fact, this method, also discussed amongst others by Wagner (2024), would enable a new type of data collection and subsequent analysis in many human and social sciences. Drawing on the power of network analysis to process this kind of network data could possibly expand the analytical treatment of both previously used and novel types of data sources. In addition, the presented methodology could be extended to the routines of reading and studying scholarly literature, enabling researchers to extract intersections with prior work and identify novel contributions in scientific articles automatically.

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Part 11 / Strand 11

Informal, Non-formal And Out-Of-School Science Education

Co-editors: *Patricia Patrick & Lorenz Kampschulte*

Part 11 / Strand 11 Informal, Non-formal And Out-of-school Science Education

Teaching and learning theories and practices in informal, non-formal, and out-of-school settings such as museums, science centres, outdoor settings, community programs (including indigenous communities), communications media, after-school programs and clubs. Includes design, adoption, exchange, and evaluation of informal, non-formal, and out-of-school learning environments, especially those organised by institutions other than schools, as well as informal and non-formal approaches to the teaching/learning of science.

Sub-themes:

1) Science Learning in Museums and Science Centers
2) Community-based Science Education Programs
3) Outdoor and Field-based Science Learning
4) Evaluation of Informal Science Learning Experiences

Contents

Strand 11: Informal, Non-Formal And Out-Of-School Science Education 985

Empowering Elementary School Teachers To Foster Students' Nature Connection: A Study Of Museum-School Collaboration For Horseshoe Crab Husbandry 988

Designing Materials Science Activities to Promote Student Engagement with Cutting-Edge Research 997

Exploring Non-Formal Science Education: Growing Crystals, Growing Minds 1007

Exploring Teachers' Objectives In Science Clubs And Beyond 1017

Exploring Science Through Play: Assessing The Impact Of The PIXEL Board Game And Its Game-Based Learning Framework On Students' NOS Perception 1026

How Citizen Science Can Support Teachers And Students In Engaging With Scientific Research: The Citizen Science School Rome Technopole 1042

What Does It Take to "Use" a Museum? A Closer Look at Museum Literacy 1049

A Scoping Review On Using Virtual Reality To Visit Informal Environments In Primary Science Education 1056

Gaining Insight Into Rural, Underserved Students' Experiences Of At-Home, Justice-Centered STEM Kits And Books 1062

Exploring the Perspectives of Families Following Their At-Home STEM Tinkering Experiences 1073

Bridging Educational Landscapes – Out-of-School Learning in Biology and Its Complementarity with Formal Curricula 1079

Strand 11: Informal, Non-Formal And Out-Of-School Science Education

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Informal And Non-Formal Science Education: Learning In Vastly Different Settings

Strand 11 encompasses the design, evaluation, exchange, and implementation of informal and non-formal learning environments and recognizes diverse approaches to science teaching and learning across after-school initiatives, clubs, communication media, community programs, digital spaces, homes, Indigenous contexts, museums, outdoor environments, and science centers. These settings provide opportunities for science engagement, identity development, and inquiry. Science learning taking place outside the classroom complements formal schooling and broadens access to scientific learning (Braund & Reiss, 2006; Falk & Dierking, 2010; Rennie, 2014). Aligned with the ESERA 2025 conference theme, Transitions in Science Education: Sustainability and Digital Advances, *Strand 11 Informal, Non-formal and Out-of-school Science Education* highlights how science learning evolves across interconnected environments and educational landscapes, spanning a wide range of life domains, it creates new points of connection for science learning and thereby fosters sustainability. The Strand 11 papers illustrate how science learning occurs during interactions among educators, institutions, families, learners, and communities across informal settings. We grouped the articles based on their locations: school-linked, museum and science centers, home-based and remote, and game-based and designed learning. The paper subsets reflect distinct educational settings and illustrate the breadth of informal and non-formal science learning represented within the strand.

School-Linked Non-Formal Programs

School-linked non-formal programs connect student out-of-classroom science engagement with curriculum and educational goals. Science clubs, competitions, laboratories, and research experiences extend science connections and provide contexts where learners engage in experimentation, inquiry, and authentic scientific practices. These environments are important complements to formal schooling because they connect science to real contexts and experiences (Braund & Reiss, 2006; Dillon et al., 2006; Hofstein & Rosenfeld, 1996; Pfeiffer & Bradbury, 2023). School-linked non-formal programs extend learning across educational landscapes beyond classroom boundaries.

Museum And Science Center Partnerships

Museums and science centers are active learning spaces where visitors engage with collections, objects, educators, and scientific practices (Falk & Dierking, 2010; Patrick, 2023). Partnerships among citizen science initiatives, communities, museums, researchers, and schools encourage participation in science (Kampschulte & Hatcher, 2021). Museums and science centers promote public inquiry and engagement and direct interactions with objects that stimulate meaning making (Preston et al., 2026; Moussouri, 2002; Patrick & Moorman, 2021; Yeh, 2023), yet at the same time allow to broaden perspectives (Knabe et al, 2025). Citizen science initiatives further strengthen connections among museums, schools, and scientific communities (Bonney et al., 2016).

Home-Based And Remote Learning

Researchers recognize home as important sites for science learning because families connect science to everyday life. Family experiences influence science engagement and shape how learners encounter science during conversations, exploration, shared activities, and tinkering (Archer et al., 2015). Family contexts contribute to developing science interest (Tenenbaum et al., 2004). At-home science activities, family support, and virtual experiences support exploration and embed science in daily experiences. Moreover, the COVID driven push in technological developments dramatically extends the possibilities of science learning at home. Virtual experiences broaden access to informal settings and provide alternatives when face to face connections are limited (Radianti et al., 2020). The authors of the study highlight the growing relationships among families, technology, and science learning.

Game-Based And Designed Learning Environments

Designed learning environments boost science engagement and inquiry. Educational design, games, and differentiated learning experiences create structured opportunities for experimentation, problem solving, and interaction with scientific ideas. Game-based learning supports motivation and conceptual understanding (Arnab et al., 2015). Game-based approaches and structured laboratory experiences shape the design of learning aids and influence opportunities for participation and learning. Games provide spaces where learners negotiate ideas, collaborate, and interact with scientific concepts. Differentiated environments promote participation during intentional design choices. Out-of-school laboratories are adaptive learning environments that reinforce authentic learning experiences and structured inquiry (Scharfenberg & Bogner, 2010).

The papers in Strand 11 demonstrate the breadth, adaptability, and continued importance of informal, non-formal, and out-of-school science education across diverse educational landscapes. Spanning school-linked programs, museums and science centers, home-based and remote learning environments, and game-based and designed experiences, the studies illustrate how science learning occurs through interactions among learners, families, educators, communities, institutions, and technologies. The contributions highlight the capacity of informal science learning environments to foster engagement, inquiry, identity development, and participation while responding to local needs and emerging educational challenges. These papers show how science learning extends beyond classroom boundaries, creating meaningful opportunities for individuals and communities to connect with science in ways that support sustainability, inclusion, and lifelong learning. As science education continues to evolve in response to digital advances and societal transitions, the research presented in this strand underscores the vital role of informal and non-formal settings in expanding access to science and strengthening connections between science, people, and their communities.

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ESERA 2025 Copenhagen

Empowering Elementary School Teachers To Foster Students' Nature Connection: A Study Of Museum-School Collaboration For Horseshoe Crab Husbandry

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Biodiversity and species conservation are core missions of science museum education, yet engaging the public with uncharismatic endangered species remains a challenge. This case study examines a 2024 horseshoe crab care program launched by the National Museum of Marine Science and Technology (NMMST, Taiwan). The program aimed to empower elementary school teachers as catalysts for fostering students' nature connection. Through a collaborative model involving specialized workshops, husbandry kits, and regular expert consultations, the museum supported teachers in integrating live-animal care into the formal 3rd-grade curriculum. The findings indicate that this partnership significantly enhanced teachers' self-efficacy; the continuous technical backing from the museum converted potential pedagogical anxiety into a sense of professional mastery. Consequently, this empowerment trickled down to students, who not only mastered science process skills but also developed a profound sense of stewardship through the long-term "parenting" of horseshoe crabs. The study culminates in a release activity, demonstrating how empowering a single teacher can create a "ripple effect" that strengthens the connection between students, parents, and the natural world. This case provides a scalable model for science museums to move beyond one-time visits toward deep, curriculum-integrated partnerships.

Keywords: Teacher Empowerment, Nature Connection, Museum-School Collaboration

Research Background

Museum's Commitment For Education

National Museum of Marine Science and Technology (NMMST, Taiwan) has been committed to promoting public attention to issues such as Taiwan's maritime environmental protection and marine life conservation. Horseshoe crabs were once a common species along the coast of Taiwan. They have become an endangered species due to economic development in the area. The Industry-Academic Exchange Group of NMMST working with Taiwan Fisheries Research Institute to restore horseshoe crabs. Though Taiwan Fisheries Research Institute develops good horseshoe crab farming technology, to rebuild wild horseshoe crab population needs more social attention for coastal environment protection and no more over fishery. It is hard to track the life of a wild horseshoe crab. The NMMST looked for schools to participate in horseshoe crab breeding program. This program hopes that through the horseshoe crab breeding project, students will pay attention to the survival problems faced by horseshoe crabs through observing horseshoe crab's life cycle.

Conservation Context: The Crisis Of Horseshoe Crabs In Taiwan

Historically, the tri-spine horseshoe crab (Tachypleus tridentatus) was widely distributed along the western and northern coasts of Taiwan. However, this "living fossil" currently faces an existential threat due to anthropogenic pressures. Rapid coastal development for tourism has resulted in the fragmentation of nesting beaches, while the expansion of aquaculture ponds has further encroached upon essential nursery habitats for juveniles. Moreover, the discharge of urban wastewater and industrial pollutants has significantly degraded the water quality of estuarine

ecosystems. These cumulative factors have led to a drastic decline in wild populations, making the conservation of this species a matter of national ecological urgency.

The Pedagogical Power Of Uncharismatic Species

In environmental education, public attention is often disproportionately directed toward "charismatic megafauna" (e.g., pandas or dolphins). However, the horseshoe crab serves as a powerful uncharismatic species for transformative learning.

Challenging Aesthetic Biases: Integrating "alien-looking" species like the horseshoe crab into the curriculum encourages students to move beyond superficial aesthetic judgments. This process fosters a deeper, more inclusive ethical stance toward biodiversity, where the value of a species is recognized through its ecological role and evolutionary history rather than its "cuteness."

Facilitating Cognitive Conflict and Curiosity: The unique, prehistoric morphology of the horseshoe crab creates a "cognitive conflict" that stimulates curiosity and scientific inquiry. By caring for a species that initially appears unfamiliar or even "ugly," students undergo a profound shift in empathy—a process that Giusti et al. (2025) describe as shifting social and spatial relationships with nature.

From Alien to Kin: As students engage in the daily husbandry of these organisms, the horseshoe crab transitions from an "uncharismatic alien" to a "vulnerable dependent." This transformation is a critical driver for nature connection, proving that emotional stewardship can be successfully cultivated even for the most unconventional representatives of the natural world.

Integration Of Citizen Science In Science And Environmental Education

Citizen science (CS) serves as a robust framework for bridging formal science education with environmental stewardship. According to Bruckermann et al. (2021), participation in urban wildlife ecology projects significantly enhances participants' scientific knowledge and fosters positive attitudes toward science, which are foundational for environmental conservation. Okada (2024) expands this through the CARE-KNOW-DO model, asserting that "open schooling" approaches strengthen the connection between scientific learning and real-life sustainability challenges. Furthermore, Bruckermann et al. (2023) found that participants' scientific reasoning skills are strong predictors of topic-specific knowledge gain. This suggests that CS provides a high-level cognitive environment where students can internalize ecological literacy through authentic scientific inquiry Bruckermann et al., 2023.

Challenges In Implementing Citizen Science Within Elementary Curricula

Despite its potential, implementing CS in primary school settings presents significant pedagogical hurdles. First, cognitive and skill-based barriers are prominent; Bruckermann et al. (2023) highlight that scientific reasoning is a prerequisite for effective learning in CS. For younger students (Grades 3–6), the complexity of data collection and systematic observation may exceed their developmental stage. Second, Atias et al. (2025) warn of epistemic injustice in school-based CS. This occurs when students are relegated to the role of passive "data sensors" rather than active contributors to knowledge construction, potentially undermining their agency and interest in science. Finally, Okada (2024) emphasizes the logistical burden on teachers, noting that balancing core curriculum requirements with the time-intensive demands of CS projects requires significant teacher empowerment and resource reallocation.

From Scientific Data Collection To Embodied Nature Connection

The integration of science and environmental education in primary schools has traditionally leaned towards citizen science models, which emphasize data contribution and scientific reasoning. However, recent scholarship suggests a critical shift toward prioritizing nature

connectedness as a more developmentally appropriate and pedagogically effective goal for young learners.

The Primacy Of Emotional And Embodied Connection

According to Lau et al. (2025), a student's sense of nature connectedness is a more powerful predictor of positive attitudes toward biodiversity than the mere acquisition of factual knowledge. This is further elucidated by Schilhab (2021), who argues through the lens of embodied cognition that learning gains are maximized when children engage in sensory-rich, physical interactions with the natural world. Unlike abstract data-driven citizen science tasks, the long-term "parenting" of live organisms (such as the horseshoe crab) allows students to develop an intuitive, embodied understanding of life cycles, which reduces the cognitive cost of learning while increasing emotional investment.

Pedagogical Feasibility For Non-Science Teachers

A significant challenge in primary science education is the perceived barrier for non-science major teachers. Harris et al. (2025) highlight that fostering nature connectedness can be deliberately developed through pedagogical strategies that focus on "care" and "experience" rather than complex scientific protocols. This approach is more accessible for generalist teachers compared to rigorous citizen science projects, which often require specialized scientific reasoning skills that may exceed the developmental stage of 3rd to 9th-grade students (Bruckermann et al., 2023).

Transformative Space And Stewardship

Giusti et al. (2025) and Graf & Debrabant (2026) emphasize that schools should serve as transformative spaces for "green transition teaching." By shifting the educational objective from being "data sensors" for adult-led research to becoming "stewards of life," teachers can facilitate a deeper relationship with nature. This shift mitigates the risk of epistemic injustice (Atias et al., 2025) and empowers teachers to lead meaningful environmental education without the need for advanced scientific specialization. Consequently, establishing a nature connection provides a more inclusive and sustainable framework for basic school science curricula.

Integrating The Horseshoe Crab Program As A Solution To Epistemic Injustice

Atias et al. (2025) argue that school-based citizen science often suffers from epistemic injustice, where students are treated as mere tools for data collection rather than active epistemic agents. This marginalization can lead to a lack of ownership and a superficial understanding of the scientific process.

The horseshoe crab care program by NMMST provides a pedagogical alternative to mitigate this issue. Unlike traditional citizen science models that focus on data contribution, this program empowers students through a stewardship-based approach. By transitioning from passive observers to active "parents" responsible for the survival of an endangered species, students are positioned as primary knowledge-holders within their classroom ecosystem. This high level of pedagogical agency aligns with Okada’s (2024) CARE-KNOW-DO model, where the emotional commitment to "care" for the horseshoe crabs drives the motivation to "know" (scientific knowledge) and "do" (conservation action).

Furthermore, by addressing the cognitive barriers mentioned by Bruckermann et al. (2023), the museum’s collaborative support enables teachers to scaffold complex scientific reasoning through tangible, daily interactions with live organisms. This transformation shifts the focus from simply reporting data to fostering a deep nature connection, thereby ensuring that students’ voices and actions are epistemically valued in the broader context of biodiversity conservation.

Research Methods

Research Design

This study employs a qualitative case study design to explore how a museum-school collaborative program empowers teachers and fosters students' nature connection. By focusing on the "Horseshoe Crab Care Program," the research investigates the transformative process of integrating live-animal husbandry into the formal school curriculum.

Participants And Context

The program involved 14 schools (8 primary and 6 junior high schools) in Taiwan. The analysis specifically highlights the experiences of elementary school teachers who acted as primary facilitators. The collaboration was structured into two phases:

Professional Empowerment Phase:

Teachers participated in an intensive workshop covering horseshoe crab biology, aquarium ecosystem establishment, water quality monitoring, and egg incubation techniques. A collaborative lesson-planning session was conducted, where teachers co-designed and submitted pedagogical plans tailored to their classroom contexts.

Implementation And Support Phase:

The museum provided essential resources, including horseshoe crab eggs and water quality testing kits. Students closely monitored the biological progression as the eggs developed through four embryonic stages before successfully hatching into first-instar trilobite larvae. Under the teachers' guidance, the students continued the husbandry process until the crabs reached the second-instar stage. At this point, the teachers facilitated the transfer of the juvenile crabs to the Taiwan Fisheries Research Institute (TFRI) for specialized long-term care until they matured into fourth-instar juveniles.

To bridge classroom learning with real-world conservation, the National Museum of Marine Science and Technology (NMMST) collaborated with the TFRI to organize the "Bringing the Horseshoe Crabs Home" release event. Teachers and students who participated in the curriculum were invited to natural sandy beaches—specifically those with historical sighting reports of the species—to release the crabs into the wild. This final act transformed the rearing process into a tangible contribution to species restoration, reinforcing the participants' identity as conservationists. It also provided an emotional milestone for teachers to reward students' dedication, offering a sense of achievement as they completed this critical stage of their environmental mission.

Conservation Action And Reflection Phase:

To conclude the program, the museum organized a series of release activities, where teachers and students returned the juvenile horseshoe crabs they had raised to their natural coastal habitats. This hands-on conservation act transformed the classroom experience from a mere biological project into a meaningful participation in species restoration, deeply reinforcing the participants' identity as environmental stewards. For teachers, the release ceremony served as a vital emotional milestone, providing a sense of closure and fulfillment. It offered a structured opportunity to reward students’ long-term dedication with a profound emotional connection to the cycle of life, solidifying the pedagogical transition from scientific knowledge to active conservation commitment.

Data Collection

To ensure a holistic understanding of the program's impact, multiple qualitative data sources were collected:

Pedagogical Artifacts: 14 teaching plans submitted by participating teachers during the workshop, reflecting their initial instructional designs and goals.

Consultation Records: Detailed logs from regular consultation meetings, capturing teachers' real-time challenges, reflections, and anecdotal evidence of student engagement.

Teacher Narratives: Qualitative feedback regarding teachers' emotional shifts, perceived self-efficacy, and observations of students' behavioral changes (e.g., patience, persistence, and stewardship).

Data Analysis

The data were analyzed using thematic analysis. Following the transcribed consultation meetings and document review, codes were generated to identify patterns related to teacher empowerment, pedagogical adaptation, and the emergence of students' nature connectedness. These themes were then triangulated across the different data sources to ensure the validity and depth of the findings.

Findings

The preliminary findings from this case study reveal a distinct pattern of teacher empowerment and age-specific student engagement, categorized into two primary themes:

1. Age-Specific Pedagogical Adaptations And Teacher Empowerment

Teachers demonstrated significant pedagogical autonomy, adapting the program to align with grade-specific curriculum goals. This adaptability highlights a key aspect of teacher empowerment: the ability to contextualize external resources effectively.

Seventh-Grade Teachers (Junior High)

These educators primarily leveraged the program to facilitate inquiry-based learning and experimental design. The investigation of variables in raising horseshoe crabs was often integrated as a structured student project, aligning with a more advanced stage of scientific reasoning [Bruckermann et al., 2023]. Some teachers noted that the standard husbandry tasks were insufficient for the cognitive level of junior high students. For instance, Teacher 1 remarked:

I feel that simply having students observe the changes in the eggs every day and record temperature and water quality data is too simple for junior high school students; there isn't much to explore.

Consequently, these educators shifted the focus toward active experimentation. Teacher 2 described their approach to experimental design as follows:

Although the Fisheries Research Institute already has the best water quality composition, I want students to be able to adjust the pH within a certain range, such as adjusting it up or down by 0.5, and see how much the egg growth period will differ.

Consequently, a divergence in pedagogical perspectives emerged: junior high school teachers viewed the horseshoe crabs primarily as experimental subjects, aiming to have students manipulate growth-related variables through controlled experiments. However, the collaborating aquaculture experts opposed treating these sensitive organisms as experimental animals for middle school students, prioritizing animal welfare and conservation ethics. In response to this constraint, the junior high teachers pivoted their strategy. Instead of structured experiments, they

established classroom aquariums and shifted the focus to a voluntary participation model. Students who showed interest could volunteer to perform daily observation, photography, water quality monitoring, water changes, and feeding, thereby maintaining engagement through long-term husbandry and documentation rather than experimental manipulation.

Third-Grade Teachers (Primary School)

In contrast, primary teachers focused on foundational science concepts. They combined the theme of horseshoe crab husbandry with the broader study of aquatic animal movements and life histories, emphasizing descriptive observation and engagement over experimental manipulation.

This interdisciplinary approach was exemplified by Teacher 4, who coordinated with various subject teachers to integrate the horseshoe crab into the third-grade curriculum:

I first asked the science teacher to use the presentation provided by NMMST to introduce the concept of horseshoe crabs to the children. Then, in the language arts class, students read a text about animal tails using teaching aids; we paired this with the museum's dried horseshoe crab specimens. Watching the children touch the different tails while describing and speculating on their functions was brilliant. Since they were unfamiliar with horseshoe crabs, I also asked the computer teacher to let them search for videos or explanations regarding their movement. After attending the workshop, the art teacher even took the initiative to use the simple mobile phone microscopes provided by the museum to have students light and photograph the crabs. ... I am very grateful for the assistance of the science, art, and computer teachers during this period, bringing a bit of the horseshoe crab into different subjects. …At the end-of-term fair, students decorated their horseshoe crab photographs on the classroom windows facing the aisle, along with simple horseshoe crab informational posters to introduce the animal to students from other classes as they passed by. I'm so proud for them.

Interviews with other participating primary school teachers consistently echoed this model of multidisciplinary collaboration, involving joint planning across language arts, science, computer science, art, and even physical education. These educators frequently expressed admiration for their students' performance throughout the process. For primary teachers, raising horseshoe crabs functioned as a pedagogical intersection for diverse subject areas. From this common starting point, students were empowered to apply their existing skills in a real-world context, transforming classroom knowledge into a tangible sense of agency. This process allowed students to experience how their collective academic competencies could be directly channeled into the active conservation of an endangered species, fostering a deep connection between their learning and environmental responsibility.

2. Emotional Investment, Skill Application, And Nature Connection

The findings strongly support the hypothesis that prioritizing nature connection is highly effective at the primary level, addressing the emotional "CARE" component of the CARE-KNOW-DO model (Okada, 2024).

Emotional Connection

Primary school students exhibited a notably higher degree of emotional investment and affective response in observing the growth of the horseshoe crabs compared to seventh-grade students. This intense emotional engagement facilitates the development of a strong nature connection (Lau et al., 2025). The depth of this bond was vividly captured in the observations of Teacher 6, who noted how students took on a parental role and extended their engagement beyond the science curriculum:

The children in my class were very proud to call themselves 'Horseshoe Crab Dads' or 'Horseshoe Crab Moms.' During the process of caring for the eggs until they grew into first-instar larvae, the first thing they did upon entering the classroom every day was check the tasks marked on the husbandry duty roster. The computer teacher also mentioned that they would proactively look for photos or videos related to the crabs' natural habitats during class. ... For the end-of-semester school fair, they even took the initiative to suggest making horseshoe crab conservation bookmarks to the art teacher, printing their photographs to paste onto conservation slogans. I never expected them to be so invested for the entire semester; even after the young crabs were returned to the Taiwan Fisheries Research Institute, their interest persisted.

Through this model of interdisciplinary pedagogical collaboration, primary school teachers expressed significant satisfaction with the profound enthusiasm ignited within their students. The educators were particularly impressed by the sustained nature of this engagement, which remained high from the initial hatching phase until the end of the semester. Furthermore, teachers acknowledged that such a complex, cross-domain curriculum would have been unattainable without the National Museum of Marine Science and Technology (NMMST). The museum's provision of specialized biological knowledge and essential physical resources served as the critical foundation, empowering teachers to venture beyond their individual areas of expertise. This partnership effectively bridged the gap between specialized marine science and classroom practice, allowing teachers to facilitate a sophisticated Interdisciplinary Learning experience that was both scientifically rigorous and emotionally resonant for the students.

Practical Skill Application

The long-term, hands-on nature of the program provided a context for practical application of scientific skills. Primary school students perceived immediate utility in foundational science skills such as weight measurement, volume measurement, and water quality testing, reinforcing the link between abstract classroom knowledge and real-world utility (Schilhab, 2021). This shift in perceived competence was also observed by the educators. Teacher 8 reflected on their initial skepticism regarding the students' ability to maintain scientific rigor in a classroom setting:

Initially, I didn't think elementary students would be able to accurately perform so many scientific process skills, such as weighing, reagent volume adjustment, and interpreting test strip reactions. Especially since they had to do it themselves in the classroom after the initial lessons, I thought they wouldn't be able to stay precise and accurate. But the horseshoe crabs actually survived and hatched. This was the first time I felt so certain that the students had truly mastered the things we taught in science class.

This reflection underscores the profound impact of authentic learning. When the accuracy of scientific skills is directly tied to the survival of a living organism, students' actions transcend mere classroom exercises and evolve into a profound sense of moral responsibility. The "empirical feedback" provided by the successful hatching and survival of the horseshoe crabs not only validates the students' learning outcomes but also significantly bolsters teachers' confidence in implementing inquiry-based instruction within primary education. This alignment between rigorous scientific practice and ethical commitment demonstrates how real-world challenges can catalyze both academic mastery and personal growth.

These findings suggest that while older students can engage in data-driven citizen science, younger students benefit immensely from stewardship-based activities that foster embodied cognition and emotional connection to nature, offering a scalable model for inclusive environmental education.

Conclusions And Implications

This study highlights the pivotal role of museums as teacher empowerees. By providing scaffolded support, museums enable non-science major teachers to lead complex conservation projects. Furthermore, the program demonstrates that when students apply science process skills (e.g., microscopy, pH monitoring, digital micro-photography) to biological restoration, they develop a positive scientific self-concept. This "stewardship-based" model offers a scalable framework for inclusive environmental education that cultivates both scientific literacy and environmental empathy.

This program demonstrated significant potential beyond student learning outcomes, highlighting the museum-school partnership model as a powerful catalyst for teacher professional development (PD). Our findings suggest that the museum's provision of expert scientific knowledge and tangible resources was instrumental in empowering primary school teachers—even those outside the life sciences domain—to successfully implement sophisticated interdisciplinary curricula.

Nonetheless, the long-term impact of this specific collaborative model on sustained teacher professional growth remains a critical area for future investigation. Subsequent research should focus on the following three key domains:

Internalization And Transferability Of Pedagogical Skills:

Future studies should track whether the teachers, post-program, can internalize the acquired interdisciplinary planning skills and scientific inquiry guidance techniques. It is essential to determine if this growth in professional capacity remains dependent on ongoing museum support, or if it successfully transfers into the educators' long-term teaching repertoire across various environmental topics.

Formation And Sustainability Of Professional Learning Communities (Plcs):

The initial "Professional Empowerment Phase" fostered collaboration and co-design among educators. Subsequent research could investigate the longevity of these museum-initiated cross-school professional learning communities. Further study should explore how the museum's role evolves from a primary resource provider to a long-term knowledge partner supporting these sustained teacher networks.

Paradigm Shifts In Educational Beliefs

Our research identified clear differences in perspective between junior high and primary teachers regarding bioethics and experimental design. Longitudinal studies could explore if sustained museum-school collaborations alter teachers' perceptions of the balance between "scientific inquiry" and "biological conservation," thereby influencing their core environmental education values and teaching methodologies.

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Designing Materials Science Activities to Promote Student Engagement with Cutting-Edge Research

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Formal education often cannot provide timely access to cutting-edge research in rapidly evolving fields like materials science, despite its relevance to urgent global challenges. Informal learning environments can bridge this gap, though challenges remain in effectively designing and integrating such experiences. This study investigates how materials science content can be educationally reconstructed and communicated through redesigned educational visits, using the Model of Educational Reconstruction (MER). Materials science researchers, science education researchers and secondary teachers collaboratively developed inquiry-based activities on biomaterials and hydrogels. Seven teachers implemented these materials, with data collected through observations and semi-structured interviews. Findings reveal that while interdisciplinary collaboration is essential, teachers serve as critical mediators due to their intimate knowledge of students' backgrounds and interests. Their reflections provided valuable insights into material effectiveness and visit design. This research demonstrates that successful communication of contemporary research requires both interdisciplinary collaboration and serious consideration of teachers' insights and recommendations.

Keywords: informal education, materials science, model or educational reconstruction

Introduction

Rapid advancements in materials science and their applications are poised to significantly impact future generations, presenting opportunities and challenges for society. These developments highlight ethical, sustainability, and educational issues that require interdisciplinary collaboration and public engagement, as seen with many emerging research topics (Ehrler, 2022). Simultaneously, advancements in materials science are revolutionizing real-world applications such as medical applications which lead to significant improvements in diagnostics, therapeutics, and regenerative medicine. Consequently, fostering scientific literacy among citizens appears essential to empower them to stay informed about scientific advancements but also to make well-informed decisions concerning their health, environment, and other critical aspects of life. In this direction, formal education in schools is expected to play an important role in shaping scientifically literate citizens. However, formal education's approach to scientific development is usually delayed, as it takes a long time before new knowledge is integrated into school curricula (Besley & Tanner, 2011).

In this context, the literature stresses the importance of informal learning spaces, such as research centers and science laboratories, which can complement formal education. These spaces are authentic environments, allowing students to come into direct contact with new knowledge, thus bridging the gap created in formal education (Berg et al., 2021). Communication strategies for cutting-edge research topics in informal learning spaces focus on the active participation of visitors, utilizing contemporary teaching approaches such as inquiry-based learning and interdisciplinary STEM approaches (Schwan, Grajal & Lewalter, 2014). Students' interaction with scientists in these settings helps to form a more realistic picture of scientific activities, while

at the same time bringing them into contact with scientific practices, enhancing their interest in related careers (Woods-Townsend et al., 2016).

However, designing and implementing educational visits to informal learning spaces requires close collaboration among experts in science content, science knowledge transformation, and science communication (Giannakoudaki & Stavrou, 2022). This interdisciplinary teamwork highlights the value of integrating various skills and knowledge areas while ensuring the creation of learning experiences that promote understanding and active engagement of students in informal learning spaces (Achiam, 2013). Teachers play a central mediating role in translating educational materials and visit experiences into meaningful learning, as they create inclusive environments, guide scientific practices, and facilitate connections between informal learning experiences and curriculum goals (Cooper & Bolger, 2024). This mediating role is strengthened through collaboration with science center staff and through appropriate preparation of students via activities that link visit themes with the curriculum (Souza et al., 2023).

Based on the above, this paper aims to develop and evaluate a series of STEM activities for informal learning spaces that focus on communicating contemporary scientific developments in the field of materials science to students. Therefore, the research question that runs through this paper is, "How can contemporary scientific knowledge be educationally reconstructed and communicated to students in informal learning contexts?".

Methodology

Research Context

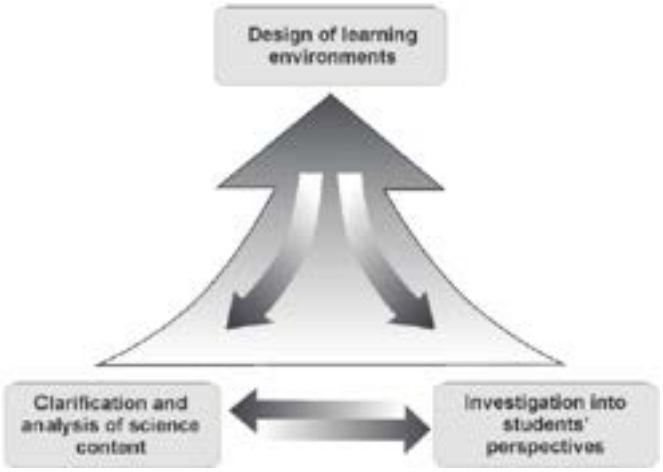
This study was carried out in the context of the MaSCot project, a 24-month cross-departmental project at the University of Crete that aimed to bring together science education researchers and materials science researchers to co-develop learning experiences in out-of-school environments to communicate contemporary scientific research topics to students. The research process was divided into three main phases. In the first phase, initial educational visits hosted in the Department of Materials Science and Engineering (DMSE) were observed to establish a baseline understanding of existing practices and identify areas for improvement. In the second phase, a learning community—consisting of experts in materials science, science education, and science communication—collaboratively developed two sets of inquiry-based STEM activities. These activities were designed to be implemented either before or after educational visits to the DMSE. In the third phase, the in-service teachers participating in the project implemented the developed materials to support educational visits to the DMSE, either as preparation before the visit or as extension activities following the visit.

Theoretical Framework

The Model Of Educational Reconstruction

The methodological framework used in this study is based on the Model of Educational Reconstruction, which consists of three components: (a) clarification and analysis of the scientific content, (b) research on teaching and learning, and (c) design and evaluation of the learning environment. These three components are not independent but dynamically interact continuously, providing reciprocal feedback (Duit et al., 2012).

Figure 1. The Model of Educational Reconstruction.



Application of MER in this Study

For the clarification and analysis of the scientific concepts, group meetings among researchers of materials science and science education were held. They collaboratively identified and discussed the key concepts that are deemed as important to be taught/presented to students. For biomaterials the concepts of biocompatibility, mechanical properties and biodegradation were found as the most prominent. As for polymers and more specifically hydrogels, key concepts relate to their composition, such as cross-linked polymerization, their mechanical and chemical properties, e.g., elasticity or viscous behavior, and the breakdown of polymers, which depends on environmental conditions such as temperature or pH.

The second component of MER, investigation of the literature, revealed several key principles for teaching and learning interdisciplinary topics such as materials science: making connections between disciplinary fields explicit, approaching topics through real-world problems, linking content to everyday experiences, and integrating theoretical knowledge into contexts that simulate authentic research practice (Li et al., 2015; Acosta, 2023; Fagnani et al., 2020).

The third component—design and evaluation of the learning environment—emerges from the interaction between the first two, involving the educational reconstruction of identified concepts using contemporary approaches to science communication. In our study, the environment reconstructed is the designed educational material to be used to frame the educational visit (before/after).

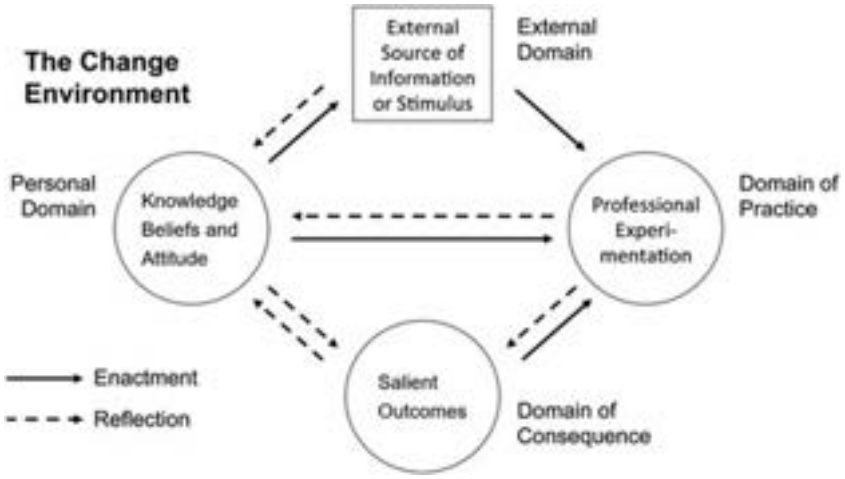
The Interconnected Model Of Professional Growth (IMPG)

Professional development is characterized by dynamic interactions across multiple aspects of teacher practice, as conceptualized in the Interconnected Model of Professional Growth (IMPG, Clarke & Hollingsworth, 2002). This framework identifies four interconnected domains: the personal domain (K), encompassing teachers' professional knowledge, beliefs, and attitudes; the domain of practice (P), representing instructional experimentation and implementation; the domain of consequence (S), which captures notable outcomes emerging from instruction; and the external domain (E), comprising influences beyond the individual teacher, including institutional factors, curricular frameworks, and professional development experiences.

These domains are connected through two mediating mechanisms: enactment and reflection. Teachers enact practice by drawing upon their professional knowledge and pedagogical orientations to inform instructional decisions, while reflection enables them to recognize and

interpret how shifts in one domain generate changes—or consolidate existing approaches—across others.

Figure 2. The Interconnected Model of Professional Growth.



The choice of IMPG in this study is based on the model's effectiveness for studying teachers' professional learning concerning the development of teaching materials in cutting-edge topics (Sgouros & Stavrou, 2019). Particularly, for the purposes of this study, the IMPG framework serves as an analytical lens for examining how teachers engaged with and evaluated the designed materials. Teacher reflections on outcomes include their direct observations of student responses to the materials and activities, offering meaningful insights into the educational value of the designed materials. Given that teachers function as critical intermediaries between instructional materials and student learning, their professionally-grounded reflections—informed by authentic implementation contexts and direct observation—provide substantive evidence for assessing the quality and impact of the educational materials.

Table 1. Framework for the analysis of current educational visits.

Axes of analysis	Categories	Sub-categories
Structure	Guidance	- Introductory presentation - Guided tour
	Role of Scientists/Researchers	• Model experiments • Explain scientific concepts • Describe potential careers
	Role of Teachers	- Accompany students - Explain concepts
Content of the visit	Scientific Concepts	- Optics & Lasers - Magnetic materials - Optoelectronics
	Scientific Practices	- Demonstration of experiments - Demonstration of equipment

Data Collection And Analysis

Data were collected using an observational protocol based on key aspects of educational visits proposed by Sajons and Komorek (2018), including the purpose of the visit, students' prior knowledge, the orientation of activities, and the roles of staff and teachers. Additionally, data were collected through semi-structured interviews with seven of the participating teachers following their implementation of the redesigned visits.

Due to the exploratory nature of the research, qualitative content analysis methods (Mayring, 2015) were employed. Observational data from the educational visits were analyzed according to visit structure and content, with inductive categories and subcategories presented in Table 1. The interview data were analyzed using the IMPG framework to identify interactions among the four domains, with analytical criteria presented in Table 2.

Table 2. Description of criteria for categorising interactions among the domains of the IMPG model.

Mediating process	Criteria	Examples
External - Personal (reflection)	The teacher reflects on the teaching material or the visit and this reflection influences or reinforces their knowledge, attitudes, etc., related to science teaching.	"In the end, I realised it — I would have preferred if we had seen the main presentation and one laboratory."
Personal - External (enaction)	When a teacher's initial perception regarding educational visits affects what is done or said during the Community of Learners meetings or during the visits themselves.	-
External - Practice (enaction)	Stimuli from the material and the meetings lead to the application or adaptation of teaching practices.	"The material was implemented in the first year of upper secondary school."
Practice - Personal (reflection)	Experience gained from implementing teaching practices leads to reflection and possible change or reinforcement of beliefs, knowledge, or attitudes.	"Perhaps the preparation should have been done differently; we should have found a way to connect things."
Personal - Practice (enaction)	The teacher's personal perceptions or knowledge influence how they carry out their teaching and how they act during the visit.	"We had a discussion; I told them some general things that I had in mind from a previous visit."
Practice - Salient outcomes (reflection)	Something that occurs during the lesson or the visit produces specific outcomes regarding the benefits for the students.	"The students were excited, they participated, they wanted to respond."
Salient outcomes - Practice (enaction)	A specific outcome influences the teacher's practices.	"And because the students were motivated, we continued during the next class hour as well."
Salient outcomes - Personal (reflection)	Observing the outcomes for the students prompts the teacher to interpret the result or to reconsider an initial perception.	"[…] perhaps it is ultimately more beneficial for students to interact with university students rather than professors."
Personal - Salient outcomes (reflection)	How teachers themselves perceive the benefits for their students.	"I think they took a step further; their horizons widened."

Findings

Analysis of the Initial Educational Visits

The analysis of the initial school visits revealed that the visits primarily consisted of an introductory presentation providing general information about the department, its research areas (e.g., optoelectronics, magnetic materials, biomaterials), and key research highlights as well as potential career pathways. Subsequently, a guided tour of the university's laboratories took place, including a demonstration of experiments and equipment by the scientists, while also explaining scientific concepts. The role of teachers was found mostly to accompany the students and, in some cases, provide additional information to help students understand the topics being discussed. The presented experiments were neither linked to innovative research activities related to the field of materials science, nor to the school's curriculum. The students were not adequately prepared by their teachers and lacked background knowledge in such specific research topics; hence, they struggled to understand the content, find relevance in the subject matter, and establish meaningful connections with scientists and their roles. Consequently, the innovative nature of the research carried out at the university, the real-world relevance of these applications, and the social implications of these issues were not emphasized.

Redesigned Visits

The structure of the visit itself was identical to the initial visits, with the addition of demonstrative experiments. The selected experiments were chosen based on the meeting discussions and what was convenient for the university to offer. The topics were polymers (specifically hydrogels and thermoresponsive polymers) and hydrophilic/hydrophobic surfaces. The specific experiments varied across visits, reflecting the dynamic nature of ongoing research and teaching in university settings where educational outreach activities are supplementary to core research functions.

The Educationally Reconstructed Material

Two sets of inquiry-based STEM activities were developed for supporting use before/after the educational visit. One of them was focusing on biomaterials and one on polymers, specifically hydrogels. Both sets follow a common structure: an introductory engagement activity, exploration of fundamental material properties, application within an authentic research context, and finally, reflection on societal and environmental connections.

The biomaterials activities were framed within a research scenario where students assumed the role of research team members developing a bone implant like applications in the DMSE. The implant was designed to function as a "bridge," providing a substrate for new bone cell growth and eventually biodegrading completely so the patient develops unified, natural bone.

Activities include: (1) an introductory task on compatibility where students selected the correct charging cable for a mobile device; (2) biocompatibility testing by counting live and dead cells in microscopy images and calculating cytotoxicity using mathematical formulas; (3) evaluating mechanical properties by comparing strength values between the implant and natural bone to determine if modifications are needed; (4) calculating biodegradation rates from mass loss data, creating graphs, and interpreting results; and (5) a reflective discussion on the ethical implications of biomaterial development and use, including the progression from initial design to animal and human testing.

The hydrogel activities began with an orientation task where students identified common characteristics in images (flexibility and water retention capacity).

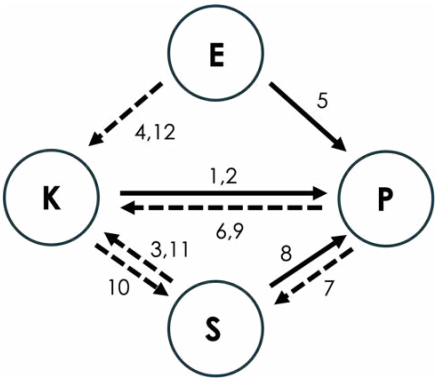
Activities included: (1) modeling polymer synthesis by connecting "macromolecules" to create networks and three-dimensional structures, then analyzing water retention mechanisms; (2)

studying absorption properties using synthetic hydrogel beads, measuring mass before and after water exposure; (3) comparing mechanical properties between natural (agar-agar) and synthetic hydrogels, observing elastic behavior under light pressure and plastic deformation under greater force; (4) examining polymer degradation under high temperature by placing both hydrogel types in boiling water and observing differences; (5) an authentic research scenario where students select appropriate hydrogel samples for different applications (wound dressings, bone implants, drug delivery systems) based on viscoelasticity measurements; and (6) a reflective activity on microplastics in various environments, prompting discussion about the environmental impact of extensive polymer use and the need for sustainable alternatives.

Teacher Case Study

To illustrate the application of the IMPG framework in evaluating the designed materials, we present a case study of one participating teacher (Figure 3). Teachers' professional reflections provide valuable evidence of material quality and effectiveness, as they possess direct knowledge of their students and observe firsthand how students engage with and respond to instructional materials in authentic learning contexts. The selected teacher taught first-grade high school students (ages 15-16) and implemented the biomaterials activity set as a follow-up activity after the educational visit to the DMSE.

Figure 3. IMPG Interactions of Case Study Teacher.



Because teachers' reflections emerged non-chronologically during the interviews, the analysis is organized by domain interactions rather than by sequence of events.

The interconnected nature of the IMPG domains is evident in the analysis above. The teacher's actions stemmed from multiple sources: external factors such as the provision of educational materials, personal beliefs and attitudes, and observations of student interest (interactions 5, 2, 8). Simultaneously, reflections on both student outcomes and on the designed materials or visit structure enhanced her attitudes toward certain practices—for example, implementing more hands-on activities—and generated new pedagogical insights, such as recognizing the value of undergraduate student facilitators with whom school students could more easily identify and connect. The impact of the designed materials is also apparent. The teacher noted that students wanted additional time to complete the biomaterials activities, as one hour proved insufficient, and highlighted the meaningful ethical discussions generated around biomaterials and science more broadly. She characterized the overall visit experience as highly successful, reporting both cognitive gains and positive shifts in students' attitudes toward science, and expressed her intention to continue such practices in the future.

Table 3. Examples of IMPG Interactions of Case Study Teacher.

Mediating process	Examples
External - Personal (reflection)	4 - The teacher chose the biomaterials activity set, citing its practical simplicity and fewer experimental requirements compared to the hydrogels set. 12- The teacher suggested increasing experimental demonstrations during the visit and allocating more time in each laboratory, noting that students expect hands-on experiences and that extended time would allow for on-site implementation of the designed activities
Personal - External (enaction)	-
External - Practice (enaction)	5- The teacher implements the biomaterials set as follow-up activity after the visit
Practice - Personal (reflection)	6- "It was very well adapted to the first year of upper secondary school and aligned particularly well with the topic of forces. For me, as a physics teacher, it integrated smoothly with the visit and provided a coherent framework." 9- The teacher reflected that a reorganisation of the programme would have facilitated the completion of the activities within one continuous session instead of two separate sessions
Personal - Practice (enaction)	1- The teacher provided general information to the students, drawing on prior experience from previous visits. 2- Regarding her actions during the visit, the teacher stated that her role was primarily learning-focused, while also ensuring smooth organisation and students' social well-being.
Practice - Salient outcomes (reflection)	7- The implementation of the material led to a discussion on the social dimensions of science and provided motivation for students to think more broadly about material properties (e.g., silicone strength).
Salient outcomes - Practice (enaction)	8- Due to students expressed interest, the teacher continued the activity in the following lesson.
Salient outcomes - Personal (reflection)	3- Students' references to biomaterials guided the discussion, leading the teacher to select the biomaterials set of activities 11- Positive student feedback, especially regarding interaction with an undergraduate student, prompted the teacher to refine her beliefs about effective mediation during visits, indicating that engagement with undergraduate students may be more impactful than interaction with academic staff.
Personal - Salient outcomes (reflection)	10- The teacher reflected that the activity, in combination with the visit, helped students make meaning of school science, allowing them to move beyond classroom learning and broaden their attitudes towards science.

Teacher Recommendations

Teachers, as key mediators between students and researchers, possess direct knowledge of their students' backgrounds, interests, and capabilities, making their recommendations essential for improving educational visits. In our study, participating teachers emphasized several priorities, as follows. Structural and procedural recommendations: i) ensuring coherence between preparatory materials and the visit itself by aligning worksheets, activities, and demonstrations with the laboratories students will encounter; ii) increasing visit duration to allow deeper engagement; iii) organizing visits around coherent scientific themes rather than broad departmental overviews; iv) ensuring early communication about which laboratories will be included to enable effective student preparation and the selection of laboratories that directly connect to classroom content. Materials and facilitation: i) providing dedicated worksheets for each laboratory station; ii) integrating authentic data and artifacts to strengthen inquiry; iii)

involving university students as near-peer facilitators; iv) ensuring that guides are familiar with teaching materials in advance.

Conclusions

The analysis of the initial school visits highlighted several key limitations, such as the weak connection between the presented experiments and cutting-edge research, as well as students' difficulties in relating the content to the curriculum due to limited preparation. As a result, the real-world relevance of materials science and its societal implications often remained underemphasized. At the same time, universities face structural constraints: they typically lack specialized staff in science communication and dedicated resources for educational outreach, while the ongoing and dynamic nature of research makes it difficult to standardize what can be presented to visiting school groups. Consequently, redesigning educational visits in a systematic and sustainable way remains challenging.

Part of the solution lies in the design of educational material to support such visits in informal learning spaces, which can act as a bridge between cutting-edge research and school science, while also helping students make explicit connections to the societal, ethical, and real-world implications of scientific research. In this context, collaboration among teachers, science education researchers, science communicators, and materials science experts is crucial for the effective design and appropriation of such interventions. Educational materials that are purposefully designed can mediate between advanced scientific content and students' prior knowledge, making contemporary research both accessible and meaningful.

As previously discussed, teachers play a central mediating role in educational visits to informal learning environments. However, introducing topics related to cutting-edge research can be demanding, particularly for less experienced teachers, who may feel uncertain or cautious when engaging with unfamiliar scientific content. This highlights the need for professional development programmes, that can strengthen teachers' confidence in these contexts. At the same time, teachers' recommendations, concerns, and experiential insights should be taken seriously, as they offer valuable perspectives for improving both the design and implementation of educational visits in informal learning environments.

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Exploring Non-Formal Science Education: Growing Crystals, Growing Minds

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In the field of non-formal science education, there are still activities that remain under researched. This is the case for crystal growth contests for school students. To address this gap, a four-year longitudinal study was designed to explore the perceptions and experiences of 165 teachers and 559 students from Aragón (Spain), who participated in such a competition. Using qualitative methods with a descriptive and interpretative scope, pre- and post-competition questionnaires containing open-ended questions that allowed participants to elaborate their responses were distributed annually. The data were analysed through qualitative content analysis, identifying categories that provided a framework for interpreting the results. The findings provide an integrated perspective of the benefits that the contest provides to participants and highlights the potential of long-term non-formal activities to bridge formal and non-formal education. Teachers reported improved pedagogical practices and enhanced professional skills, and students gaining a deeper understanding of scientific processes and developing different skills. Students found the competition enjoyable and rewarding, which improved their knowledge and perception of science, provided them with some practical experience, and promoted their skills. Additionally, the relaxed setting fostered stronger teacher-student relationships, contributing to a more engaging and collaborative learning environment. These findings offer valuable insights for designing more effective educational initiatives and provide a foundation for future research on the role of long-term non-formal activities in science education.

Keywords: crystal-growing competition, student perceptions, teacher experiences

Introduction

Non-formal education in the field of science has experienced very strong development over the last decades, primarily because it is less constrained by limitations typically associated with traditional classroom settings. As a result, non-formal education has emerged as a means of extending and enriching both students' and teachers' experiences. These experiences support science learning in ways that traditional schooling cannot (Kisiel, 2014) and address aspects of science education that are often absent in formal education (Jarvis & Pell, 2005).

The literature (e.g., Affeldt et al., 2017; Burke & Navas Iannini, 2021; Nuora & Välisaari, 2018) shows how non-formal teaching is recognised as an element that contributes notably to lifelong learning (Woithe et al., 2022) and provides different types of benefits to participants that are mutually reinforcing, highlighting that such experiences offer various cognitive, procedural, affective-emotional, personal, and social benefits to participants. Indeed, research also demonstrates the positive impact of these activities on teachers in terms of professional development and training.

1. *Cognitive Benefits.* They allow students to be exposed to learning conditions that simply cannot be reproduced in the classroom (Nadelson & Jordan, 2012), thereby providing additional support for learning. Along the same lines, they act as a bridge between knowledge acquired at school and outside of it, promoting the acquisition of new content, concepts (Canovan, 2019; Domenici, 2022), and models (Bell et al., 2009) from a more interdisciplinary perspective (Yu & Yang, 2010). In this way, they not only foster a greater understanding of how scientific knowledge is generated and constructed but also have a

positive effect on academic performance (Miller et al., 2018). Finally, they offer opportunities for students to develop skills, attitudes, and values normally associated with science (Weinberg et al., 2011) and develop their cognitive abilities (Julien & Chalmeau, 2022).

2. *Affective Benefits*. They foster students' interest and curiosity in science (Weinberg et al., 2011) and increase their motivation towards both science itself (Markic et al., 2017; Tisza et al., 2020) and its learning (Affeldt et al., 2015; Raaijmakers et al., 2021). Furthermore, they promote, develop, or generate more positive attitudes and feelings (Nuora & Välisaari, 2018) towards science and its learning, thereby enhancing the appeal of science education and generating positive emotions towards the sciences (Canovan, 2019). Consequently, they have the capacity to induce changes in participants' attitudes towards science (Millar et al., 2019) and contribute to increasing the perception of the social relevance of science and students' commitment to science (DeWitt et al., 2018). Finally, they contribute to the generation of a scientific identity (Burke & Navas Iannini, 2021) and the promotion of scientific vocations (Jones et al., 2011; Wünschmann et al., 2017) and professional orientation towards science careers.

3. *Social Benefits*. They contribute to socialisation because they bring students with common interests into contact, which allows for the generation of a certain sense of community belonging (Millar et al., 2019) where they can be recognised by themselves and others as people of science, which also aids in the consolidation of a scientific identity (Burke & Navas Iannini, 2021).

4. *Benefits for Teachers*. They promote professional reflection and identity (Haatainen et al., 2024) and support teachers in their professional development (Gupta & Adams, 2012; Martín-García et al., 2024). In this sense, they provide an opportunity to broaden, enrich, and diversify teacher training by offering motivating structures for learning and opportunities to practise science teaching in "safe" environments (Avraamidou, 2014; Martín-García et al., 2024). This helps them develop greater confidence in their abilities as educators and improve their self-concept and self-efficacy when teaching science (Martín-García & Dies Álvarez, 2024). Therefore, they contribute to the development of both scientific-content knowledge (Jung & Tonso, 2006) and pedagogical-content knowledge (Kisiel, 2013). Finally, they also help them acquire a greater understanding of the characteristics of their students (Tang et al., 2017).

Knowing these benefits, educational research has long advocated bridging formal and non-formal education (Fallik et al., 2013; Molz et al., 2022; Watermeyer, 2015). However, much of the existing research has focused on short-term, non-formal activities, such as museum visits led by external educators (Avraamidou, 2015). In contrast, the present study centres on a long-term, academic-year-long activity coordinated and implemented by teachers themselves, without the intervention of external educators. This allows for a more direct link between formal and non-formal experiences and helps identify how these experiences relate to the curriculum content and how to integrate them effectively into their lessons

The Present Study

Non-formal education in science is an extraordinarily broad and heterogeneous reality that is difficult to categorise, encompassing highly diverse activities conducted in various contexts and with differing durations and developments. For instance, non-formal activities range from visits of a few hours to specific locations led by external educators, to projects lasting several months

where the work is carried out directly with the teacher, such as in science clubs (Martín-García et al., 2025).

Within this second category, we find the so-called crystal-growing competitions for schoolchildren (Whelan et al., 2018), which have been celebrated with great success worldwide (Perret et al., 2014; Van Meervelt, 2014). These are global events organised at a European and international level by the International Union of Crystallography. These events provide an opportunity for students to operate as 'scientific researchers', to investigate something they are curious about, design and implement experiments, collect data and extract meaning from them, draw evidence-based conclusions from the obtained results, and present and explain them to others. The one and only condition is that the projects must include some crystal-growing experiences.

Nevertheless, there is little research that provides empirical evidence concerning crystal growing competitions, as there have been no systematic studies of their implementation and outcomes. Furthermore, prior research seems to be scattered through isolated publications that are generally based on personal anecdotal opinions and subjective perceptions from the organisers rather than data and evidence gathered through research (Perret et al., 2014; Van Meervelt, 2014). This article aimed to fill that gap by providing evidence-based information derived from a four-year longitudinal investigation.

In Spain, crystal-growing competitions are now celebrated all over the country with several regional editions that culminate in a national final. Specifically, in the region of Aragón, where the study focused, the contest, named *Concurso de Cristalización en la Escuela de Arag*ón (CCEA), has held ten editions, reaching more than 10,000 students and over 140 schools from both urban and rural areas.

The contest is divided into three stages, covering almost the entire academic year: an initial stage where the competition, its organisation, development, and functioning are presented to the teachers; a second stage where the students work on their crystallisation projects supervised by their teachers; and a third stage in a congress format where representatives from each school defend their project before a jury of experts and the public attending the final. It is also mandatory for each team to elaborate a scientific poster summarising the project and its conclusions and to exhibit their laboratory diaries as well.

The contest's main objective is to raise students' awareness of science, increase their interest in it, encourage them to participate in scientific activities, and develop their scientific skills and abilities. The competition offers students an opportunity to immerse themselves in scientific investigations as if they were scientists, to design and conduct their own research projects, implement experiments, collect data, and make evidence-based decisions.

Method

Despite the crystal growing competitions have been held worldwide for years, there is a notable lack of empirical studies addressing their formative potential or their impact on teachers and students who participate in them (Van Meervelt, 2014). Consequently, this research was designed with an exploratory and descriptive nature, aiming to understand the experiences and perceptions of those involved in such competitions. Therefore, to align with this objective, a qualitative methodology with an interpretative focus was adopted to give participants a voice and allow their perceptions to be studied directly.

Previous studies (e.g., Garner et al., 2015; Karnezou et al., 2021) indicate that one of the objectives most frequently pursued by educators participating in non-formal activities, at least in

the field of science, is precisely to connect the activity with the school curriculum, often being the main reason for determining which activities or projects have potential interest. Building on this basis, the research also aims to analyse how the competition activities fit within the secondary curriculum framework, by analysing the secondary education curricula to determine which of their elements can be addressed within the scope of the contest activities.

In this way, the perspective "from within" offered by the participants' impressions and experiences is complemented by an analysis "from without", conducted using the official normative documents that regulate secondary education in the region of Aragón.

To analyse the participants' perspective, a longitudinal study was conducted between 2016 and 2020, involving 165 teachers and 559 students from various towns in Aragón. For data collection, two ad-hoc open-ended questionnaires were designed each year for the teachers and two for the students: one administered prior to the competition and one afterwards. These questionnaires included open-ended questions that required the participants to construct their own responses, and they were specifically developed for the research and adapted to the context. The first questionnaire was distributed before the experimental phase began. The second, in contrast, was administered once this second phase had concluded but always before the competition final. Both were administered via the Google Forms platform to facilitate the subsequent analysis process.

The textual information contained in the respondents' answers was analysed using content analysis procedures. Specifically, strategies typical of Qualitative Content Analysis (Mayring, 2022) were employed by applying a semantic approach that allowed the identification of codes based on explicit meanings in the data. That is to say, the object of the analysis was not so much the style, composition or the organisation of the discourse, but rather the meanings contained within the transmitted message. This process allowed for the inductive generation of sets of categories representative of the participants' perceptions, providing an explanatory framework from which to interpret participants' responses and comprehend the underlying background. This analysis process was carried out in duplicate: first by considering the responses from each year separately, and subsequently from a more general perspective, considering the responses from the different editions as a whole.

Finally, for the studies focusing on the curriculum, documentary analysis strategies were used (Wotring et al., 2021) on the orders that specify the curriculum. This was done to locate, fix, select, and give meaning to the data collected in these documents, thereby allowing the researchers to discover and describe the central axes and main themes of the curriculum.

Findings

The responses from the teaching staff describe the competition as a beneficial learning context for students, where they can have fun and enjoy themselves, while acquiring knowledge across various subjects and developing a range of skills. Similarly, they regard it as an opportunity to foster a deeper understanding of scientific phenomena and explore science, scientific work, and research. Additionally, the contest is considered beneficial for teachers themselves, as it provides a chance to enhance their professional competencies and improve their role as teachers.

On the other hand, students perceive the competition as an opportunity to gain new knowledge and engage in laboratory work alongside their peers. Many also acknowledge that it has improved their perception of science, as they have discovered it to be more appealing, interesting, less abstract, and more accessible. In terms of content, curriculum analyses indicated that the contest allows for the inclusion of both specific topics and complete blocks of content from various subjects.

Specifically, seven key aspects summarising their perceptions of how the CCEA can contribute to science education have been established from the participants' responses. In this regard, the participants perceive the competition as an opportunity to:

1. **Improve Students' Scientific Education**

Teachers described the competition as an effective tool to foster students' scientific education because it allows them to address content from different subjects and, at the same time, go a step further than the curriculum and work on topics not explicitly included in the normative documents. Similarly, the students acknowledge specific learning achievements, both in the field of crystallisation and in relation to the curriculum of various subjects. The systematic curriculum analysis not only corroborates these perceptions but also reveals how other curricular elements exist that can be worked on beyond those mentioned by the participants. Furthermore, teachers emphasise the competition's ability to integrate knowledge from different disciplines, which allows for offering students an image of scientific knowledge as something that is coherently interrelated. Finally, it also provides an opportunity to promote the development of students' competencies, particularly their scientific competence.

2. **Develop Students' Skills**

According to teachers, participation in the competition provides students with opportunities to develop skills that are challenging to cultivate in traditional classroom settings. These include scientific skills, such as analysing and interpreting data, as well as transferable skills such as teamwork, which are highly valued by both teachers and students. In the case of the students' responses, they highlight how they have not only learned to work as a team but also to plan and organise that work.

3. **Provide Students with A More Realistic Image of Science**

Students feel that participating in the competition provides them with more realistic insight into how experimental sciences operate. They have come to appreciate key aspects, such as the importance of methodology, the need for replicability, and the broader role of science in society. Teachers emphasised that the contest helps students develop a more accurate understanding of how scientific knowledge is created and validated. In this way, students can appreciate the sometimes tentative nature of science and move a little closer to understanding its nature.

4. **Offer Students an Enjoyable Experience in Science**

Many teachers participate in the competition to reward their students by offering them an enjoyable and engaging experience that can help reduce the feelings of stress or anxiety that science sometimes generates and substitute them with a more positive emotional bond that may make students more willing to engage with it. This approach seeks to create a positive emotional connection with science, foster improved attitudes towards the subject, and boost motivation. Students confirmed that they perceived the competition as both rewarding and fun.

5. **Promote Teacher Professional Development**

Teachers regard the competition as an opportunity to complement and extend their training and support their professional growth. Specifically, they acknowledge that the competition is a way to come into contact with new ideas and highlighted that the competition equips them with additional resources and teaching strategies to enrich their educational toolkit. In this sense, they consider that they have gained practical knowledge for their daily teaching practices as well as insights that broaden their scientific understanding especially, but not only, in the field of crystallisation. Moreover, teachers described how the experience has allowed them to better understand the students and become more aware of their abilities and needs, which is very useful

when planning and guiding classroom teaching. Finally, they acknowledge that participation in the contest serves as a source of motivation and personal satisfaction because they believe they are doing something beneficial for the students, which encourages them to become involved in other non-formal education activities.

6. Test New Science Teaching Strategies

Teachers view the contest as an opportunity to rethink their teaching practices, giving greater importance to practical laboratory work. They also see it as an opportunity to explore different teaching-learning contexts and situations and a platform for innovation, allowing them to experiment with new methodological approaches and to assess their effectiveness. Consequently, they feel more confident in applying these approaches in the classroom and feel more capable of teaching science.

7. Strengthen Personal Relationships

The findings revealed that the contest fosters a conducive environment for strengthening the bond between teachers and students. In this sense, there is an almost unanimous consensus among teachers in pointing out that the interactions established with students during the sessions dedicated to the contest differ significantly from those habitually generated in the classroom. The more relaxed atmosphere of the event, coupled with students' increased motivation, created a climate of trust and enhanced communication. This enables teachers to gain a better understanding of their students, contributing to a more enjoyable and fulfilling experience for everyone.

Discussion

The findings of this four-year longitudinal study emphasise the significant educational value of crystal growth contests for both teachers and students. The perceptions of participants reveal that the competition is a mutually beneficial experience for both of them alike. For students, it fosters engagement, skill development, and a deeper understanding of science. For example, they themselves highlight the effect of the contest on their image of science and science subjects, acknowledging that this has improved, in some cases because they have discovered a more appealing, entertaining, or interesting science, and in others because they have discovered a less abstract, less complicated, and more understandable science.

For the teachers, it supports professional growth and innovation in teaching practices while it contributes to promoting their content-knowledge, their pedagogical-knowledge, and their knowledge of the students, their characteristics, needs, and motivations. Finally, from the curricular perspective, it is clear that the contest allows for addressing specific content or knowledge in a simple and integrated manner, but also complete or practically complete blocks of the curriculum from different subjects belonging to different areas of knowledge.

However, the development of the contest is not free of problems or situations that must be confronted or resolved, which have led teachers to question certain aspects of it because they do not fully align with their vision of what the project should be. There are other aspects that, in the teachers' opinion, should be rethought or modified; these mainly refer to organisational aspects and not so much to how the contest is conceived or the effects it has on the participants, which are perhaps the most interesting aspects for the research. Thus, the results highlight the multifaceted benefits of participation that extend well beyond disciplinary knowledge to encompass broader educational and developmental outcomes.

These results broadly align with existing research (Affeldt et al., 2017; Burke & Navas Iannini, 2021; Karnezou et al., 2021; Molz et al., 2022; Raaijmakers et al., 2021), highlighting the critical

importance of integrating formal and non-formal education to enhance the teaching and learning of science and ensure equitable benefits for all students. However, this study introduces several distinctive contributions that enrich the current understanding of such educational experiences and deepen our understanding of their role in science education.

First, it addresses an activity that, despite its global implementation, has been largely overlooked in prior research. Second, the focus on long-term initiatives marks a departure from the predominantly short-term activities typically examined in the literature. Third, the study adopted a multi-perspective approach to explore the experiences of both teachers and students. This approach, although uncommon, is essential for providing a holistic understanding of educational impact. Finally, the longitudinal design is particularly noteworthy, as studies of this nature remain scarce in the context of non-formal science education activities.

Collectively, these results represent a valuable contribution to the field of non-formal science education, offering new insights into the potential of these activities to enrich both teaching and learning. It is notable that the results of such diverse research, conducted in such different contexts, present so many marked similarities regarding the benefits that non-formal activities offer. This convergence suggests that the elements that are repeatedly observed are crucial for understanding the true significance of participation in non-formal activities for both teachers and students and that these are the aspects that should be attempted to be transferred to the classroom as much as possible.

Conclusions

In synthesis, the School Crystallization Contest, due to its nature as a non-formal activity, its development, the mode of work it promotes, and the final congress format as the culmination of the research and experimentation processes, brings together the best of three worlds:

1. The broad spectrum of possibilities offered by non-formal education, as it involves fewer limitations than formal education.
2. The benefits of methodologies based on inquiry, laboratory work, collaboration with peers, autonomy, and motivation.
3. The complementary nature of public science communication experiences.

The project harmonises these three elements to achieve greater scientific literacy among students, a greater understanding of science and its knowledge, and to continue training science teachers by improving their professional performance. In this process, the experience contributes to fulfilling curricular objectives, to the development of the key competencies that structure the curriculum in Spain and facilitates the addressing of content from different subjects from a multidisciplinary perspective, which rightfully makes the contest an extremely comprehensive training tool.

Therefore, these findings serve as a basis for future research, but also for the development of non-formal education programmes that are more enriching and attractive for teachers, who ultimately decide whether or not to integrate them into their classroom practice. However, beyond their academic value, they also have practical value because they offer the community a clear example of what participation in non-formal education activities can entail in terms of training and personal and professional development.

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Exploring Teachers' Objectives In Science Clubs And Beyond

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Despite the value that teachers place on non-formal activities, their goals and what they need from them remain underexplored, particularly in the context of long-term initiatives. In this work interviews with 19 teachers coordinating school science clubs in Portugal were conducted and their key objectives for the implementation of the club in the school were analysed. These include bringing science closer to students and communities, connecting activities with the curriculum, fostering scientific and interdisciplinary skills, and enhancing student motivation and engagement. In parallel, a literature review was conducted to identify studies examining teachers' goals for non-formal education activities. Thirty relevant studies were analysed, and their findings were compared to the objectives identified in the context of science clubs. The results revealed that teachers coordinating science clubs recognised all the goal types highlighted in the literature but placed greater emphasis on certain objectives which are less frequently mentioned in other types of non-formal activities. The findings underscore that science clubs enable meaningful experiences that complement traditional teaching, fostering interdisciplinary connections and promoting scientific literacy. The study concludes that understanding teachers' beliefs and requirements is crucial for designing activities that not only complement the curriculum but also address challenges within the formal education system. Greater integration between formal and non-formal education can generate synergies, bridging gaps and creating a seamless continuum of experiences that enrich science teaching and learning.

Keywords: non-formal education, science clubs, teachers' goals.

Introduction

There is growing evidence that students' knowledge and understanding of scientific concepts develop across a variety of settings, both within and beyond the classroom (Mujtaba et al., 2018). The benefits of non-formal learning environments for school students have been widely studied in many countries, showing that these activities make significant contributions to science teaching both in the conceptual-cognitive and affective-emotional domains (e.g. Aslan et al., 2023; Haatainen et al., 2024). As a consequence, it has been acknowledged that non-formal learning experiences can support science learning in ways that traditional schooling cannot overcome (Covert et al., 2019; Kisiel, 2014).

Nowadays, teachers increasingly recognise the value of non-formal learning spaces in providing educational experiences for their students (DeWitt and Osborne, 2007). Therefore, the effective integration and utilisation of these environments in science teaching represents an essential step toward fostering a more comprehensive and impactful approach to science education.

The role played by teachers in the integration of formal and non-formal education cannot be denied. Research firmly suggests that teachers and their approaches to non-formal learning play a crucial role in determining the effectiveness of such experiences (Luehmann and Markowitz, 2007; Uppin and Timoštšuk, 2022). Particularly critical is the value teachers attribute to these activities in enhancing their students' learning and abilities, as well as the goals they have for the experience, and the potential such activities offer to establish meaningful connections with the school curriculum (Karnezou et al., 2021). Despite their importance, these factors are often

overlooked and limited emphasis has been placed on understanding teachers' perceptions, particularly in the context of long-term scientific activities (Martín-García et al., 2024).

For this reason, understanding teachers' beliefs regarding non-formal activities, what they need, and what they are looking for when entering the world of non-formal education is essential for designing activities that are both effective and responsive to their demands. However, achieving such interrelations and complementarity is considerably more feasible when activities are designed and implemented by teachers themselves and extend throughout the academic year. Examples such as science clubs illustrate this point effectively, as they allow for frequent and meaningful connections between non-formal activities and classroom learning. In Portugal, there is an established network of science clubs known as the "Clube de Ciência Viva na Escola" (The Alive Science Club at School), initiated and supported by the Ministry of Education. Within this framework, science teachers working at participating schools are responsible for coordinating science clubs. Such activities enable a seamless transition from classroom knowledge to application in a non-formal setting, or vice versa, facilitating experiential learning and the construction of knowledge in both contexts (Martín-García, Afonso, et al., 2024; Martín-García, Dies Álvarez, et al., 2024).

The focus of this study is to explore the specific goals established in the context of science clubs, with their unique characteristics, and compare them to the goals set for other types of non-formal education activities. To complement this analysis and establish comparisons with other types of non-formal activities, we conducted a review of 39 studies that explored teachers' objectives and expectations regarding various non-formal education activities to identify the types of objectives typically mentioned by teachers and whether these differ between short-term and long-term activities.

Method

This study is part of a broader investigation examining science teachers' subjective perceptions and experiences with school science clubs in northern Portugal. Following the previously described objectives, the study comprised two main parts: a literature review and a qualitative study using semi-structured interviews. Firstly, a bibliographic search was conducted in the Web of Science database to identify articles addressing the objectives, intentions, and expectations of teachers regarding non-formal education activities. Following a review of the titles and abstracts of the retrieved references, studies explicitly outlining the specific objectives set by the teachers were selected. Finally, the studies were classified based on the type of activity they described, and whether they were short- or long-term initiatives.

In parallel, we were interested in the evaluation of the perspectives of the teachers who coordinate science clubs regarding their goals, expectations, or intentions towards non-formal education. The analysis of teachers' perspectives in the literature often relies on closed-ended questions, which do not allow for a detailed understanding of their views, thus limiting their validity (Jensen and Buckley, 2014). In contrast, in this case, we approached the study using semi-structured interviews with 19 teachers who coordinated school clubs in the northern region of Portugal. The interview script conformed to a set of open-ended questions to invite teachers to elaborate on their answers.

Both the literature findings and the interview transcriptions were analysed using inductive bottom-up content analysis from a semantic perspective. This meant that our codes were directly derived from the data rather than imposed based on an a priori framework (Mayring, 2022). We then grouped codes with similar meanings to generate categories until we had a set of categories that were representative of the types of goals mentioned by the teachers in each case. This set

provided an explanatory framework which allowed interpretation and comprehension of their responses.

Findings

The search yielded 30 studies that mentioned concrete objectives for participating in non-formal educational activities. Of these, 22 studies focused on short-term activities, while only 7 examined long-term projects. The study by Tisza et al. (2020) spans several types of activities with differing durations, making it unsuitable for classification under a single category. Specifically, the studies on short-term activities were primarily focused on the context of museums (18 studies), of which 16 were developed as school field trips. Works carried out in outreach laboratories (2 studies) and science festivals (2 studies) also appear. Finally, one of the studies discusses field trips in general, without specifying the type of location visited. Regarding long-term activities, science fairs predominate (3 studies), but there is also mention of projects conducted in aquariums (1 study), crystal growth competitions (1 study), and enrichment programmes (1 study), and even in a science club (1 study). The analysis of these studies allowed us to generate several categories, as summarised in Table 1, which describe the primary types of objectives identified in these studies.

Table 1: Types of objectives for non-formal education activities mentioned by teachers in the 30 selected studies from the literature review. Number of studies conducted in short-term and long-term activities that mention each of the objectives (percentage of the total number of studies conducted in short-term or long-term activities).

Code	Objective focused on	Number of articles	Short-term (n=22)	Long-term (n=6)
O1.	Increasing students' exposure to science	16	10 (45,5%)	5 (71,4%)
O2.	Science content-knowledge	18	12 (54,5%)	5 (71,4%)
O3.	Curriculum connection	14	12 (54,5%)	2 (28,6%)
O4.	Providing new learning experiences	17	14 (63,6%)	3 (42,9%)
O5.	Experimental work experience	10	7 (31,8%)	3 (42,9%)
O6.	Developing of students' skills	9	3 (13,6%)	5 (71,4%)
O7.	More effective teaching	12	7 (31,8%)	5 (71,4%)
O8.	Exposing the students to what the settings uniquely have to offer	9	8 (36,4%)	1 (14,3%)
O9.	Personal interest of the teacher or school demand	8	6 (27,3%)	2 (28,6%)
O10.	Motivation and interest	18	14 (63,6%)	3 (42,9%)
O11.	Enjoyment and engagement	13	12 (54,5%)	1 (14,3%)
O12.	Personal relationships and interactions.	9	7 (31,8%)	2 (28,6%)

Note: Cells shaded in purple indicate content-oriented goals, cells shaded in green indicate affective-oriented goals, and cells shaded in red refer to general education-oriented goals. The total number of objectives does not match for objectives O.1, O.2, O.6, and O.10 because these are the objectives mentioned in Tisza et al. (2020) study, which refers to all types of activities without specifying duration.

The review of the literature reveals a broad range of objectives, suggesting that non-formal activities can serve diverse purposes and address various educational needs. The revised studies include more cognitive objectives, focused on the acquisition of specific scientific knowledge, but also more affective objectives, centred on areas such as motivation, enjoyment, and interest in science. Furthermore, objectives more focused on the immediate educational context also feature, relating to the teaching and learning process, such as the curriculum, the teaching practice, and the type of educational experiences to which students are exposed.

The most commonly mentioned objectives include the acquisition of scientific knowledge and content, as well as the enhancement of student motivation and interest. Additionally, many studies have emphasised the provision of new learning opportunities and exposure to science in ways that allow students to engage more deeply. These findings underscore the teachers' emphasis on connecting non-formal activities with the classroom, whether as complements, extensions, reinforcements, or applications of classroom learning, targeting both subject-specific knowledge and the development of skills and attitudes.

Reviewing short-term and long-term activities separately reveals that all categories derived from the literature analysis are mentioned in both groups. However, there are differences in the types of objectives most frequently cited. For example, in long-term activities, the dominant objectives are "*To increase their exposure to science*", "*Science content-knowledge*", "*Development of students' skills*" and "*More effective teaching*", which appear in 5 out of the 7 articles contextualised in long-term activities (71.4%). In contrast, in short-term activities, the predominant objectives are "*Providing new learning experiences*" and "*Motivation and interest*", appearing in 14 out of the 22 studies found (63.6%). To a lesser extent, "*Science content-knowledge*", "*Curriculum connection*" and "*Enjoyment and engagement*" stand out, being mentioned in 12 studies (54.5%).

The qualitative findings derived from interviews with teachers who coordinated science clubs show that they set a wide variety of different goals for the clubs. The responses could be organised into seven categories, but within the majority of them, several different themes can be identified. Both the categories and the most relevant themes found within them are summarised in Table 2. It is important to note that these categories are not mutually exclusive. More often than not, teachers expressed several goals, and some of them may be classified in more than one category. In fact, all 17 interviewed teachers identified more than one category of objectives. Specifically, three teachers mentioned two categories, three mentioned three categories, nine mentioned four categories, and three mentioned all five categories. This demonstrates the multifaceted nature of these objectives.

Overall, teachers coordinating science clubs recognised all the types of objectives discussed in the 30 reviewed references. That is to say, the goals declared by the teachers are, for the most part, quite similar to those found in the literature. In both cases, objectives aimed at providing concrete benefits to students or improving their learning of science predominate. Table 2 illustrates how the categories constructed in the interview analysis relate to the types of objectives found in the literature review. However, differences are also observed, for example, in the relevance given to the learning of disciplinary content or science. For this reason, our interviews reveal some unique aspects that differentiate the clubs from what is typically reported in the broader literature.

Firstly, it became evident that teachers see the science club as an opportunity to integrate concepts in broader contexts and engage in interdisciplinary activities, a goal that appeared in only one of the 30 references analysed. Secondly, these teachers place strong emphasis on the opportunity to integrate concepts in broader contexts and engage in interdisciplinary activities. This was

particularly striking as this specific goal appeared in only one of the thirty analysed references. Finally, teachers placed greater emphasis on goals related to bringing science closer to the community and students—a key objective present in all interviews and thus fostering community and student appreciation of the club's role in promoting science education, an objective that was not captured in the 30 references.

Table 2: Types of objectives mentioned by teachers coordinating science clubs in the interviews: categories, subcategories, and number of teachers mentioning them. Relationships or associations with objectives derived from the literature review analysis (n=17).

Category	Subcategories	Number of teachers	Associated objectives from the literature review
To bring science closer to pupils or the community	Disseminate the study of science. Motivate students and engage them in scientific activities. Promote scientific literacy and scientific culture. Showing that science is important to society.	17	O1.; O2.; O3.; O4.; O10.; O11.
To promote other means of teaching and learning:	Providing interdisciplinary experiences. Connecting with the curriculum. Experience the experimental component of science.	14	O1.; O2.; O3.; O4.; O5.; O7.; O8.; O9.
To develop students' skills and abilities	Scientific skills. Cross-disciplinary skills.	13	O5.; O6.; O9.; O12.
To increase awareness about what the club offers	Supporting students with difficulties or high abilities.	6	O1.; O2.; O3.; O4.; O5.; O6.; O7.; O8.; O9.
To increase students' science content-knowledge		12	O2.; O3.
To promote or improve personal relationships and interactions.		2	O6.; O12.

Discussion

The main aim of this study was to examine the specific goals set within the context of science clubs and to compare them with those established for other types of non-formal education activities. Previous studies in this field seems to be somewhat contradictory. Some studies reveal that although schools and teachers attribute high value to the museum visit, the international literature indicates that teachers hardly define their goals for the museum visit (e.g. Cox-Petersen et al., 2003). For example, Tal et al., (2005) studied 30 teachers in four natural history museums in Israel. They found out that only one-third of these teachers provided specific purposes for

conducting the museum visit, explaining how the visit was connected to the school curriculum. Most of the teachers gave general answers about the purpose of the visit, while in many cases teachers stated that others had planned the visit and they were unaware of the purpose. On the other hand, other publications reported that teachers seem to have multiple objectives for activities such as fieldtrips which include both cognitive and affective elements (Anderson et al., 2006; Karnezou et al., 2021; Martín-García and Dies Álvarez, 2022). Other works have also shown how teachers articulated their goals around these two dimensions (e.g. Canovan, 2019; DeWitt and Storksdieck, 2008; Tisza et al., 2020).

The results obtained in this work, both in the literature review and in the teacher interviews, align more closely with these latter studies. Specifically, the analysis of the references found in the literature review evidences that teachers recognise the role such places can play in providing unique educational experiences for their students, both when dealing with short-term and long-term activities. Consequently, they generally establish certain objectives for the activities, although these may sometimes be very generic.

The interview results are generally consistent with the findings derived from the systematic analysis, although they do show certain slightly distinct elements that have not been recorded in the studies analysed in the literature. However, it has not yet been possible to determine whether these elements are inherent and exclusive to the science club as a non-formal education context or whether they are more related to the sustained, long-term nature of the activities carried out.

In any case, given the complexity and diversity of activities encompassed within the domain of non-formal education, teachers' objectives in out-of-classroom learning environments are far from uniform. However, although the activities and their contexts differ, there are some noteworthy similarities with regard to teachers' declared goals. It is notable that the results of such diverse research, conducted in such different contexts, present so many marked similarities. This convergence suggests that the elements that are repeatedly observed are crucial for understanding the true significance of participation in non-formal activities for teachers and that these are the aspects that should be attempted to be transferred to the classroom as far as possible.

There are no major differences between short-term and long-term studies regarding the types of objectives proposed by the teachers. In fact, as indicated, the reviewed studies, as a whole, mention all the categories emerging from the analysis, both when considering only the short-term activities and when considering only the long-term ones. However, our review revealed that much of the existing research has focused on short-term activities such as school field trips, where external educators often lead educational initiatives. In contrast, we identified only two studies that examined long-term activities, where teachers take on responsibility for leading the activities themselves (Longhi and Schroeder, 2012; Martín-García and Dies Álvarez, 2022).

There is growing evidence that students' knowledge and understanding of scientific concepts develop across a variety of settings, both within and beyond the classroom. Therefore, teaching science in the classroom environment should be supported with experiences gained outside the classroom (Aslan et al., 2023). Thus, the appropriate and effective use of non-formal activities in science teaching is very important and it should become a core practice rather than something that teachers do when they have extra time. For that reason, understanding how teachers' beliefs regarding non-formal activities are structured—what they need, seek, and value when engaging in non-formal education—is essential for designing activities that are both effective and responsive to their demands. Activities that truly align with teachers' expectations are more likely to be meaningful and impactful.

For this reason, we agree with authors such as Luehmann and Markowitz (2007) who declare that much can be learned about secondary science classrooms' needs by considering teachers' perspectives because by considering both educators' perspectives, we gain a clearer understanding of the practice. In other words, by considering these perspectives, we gained valuable insights into the perceived gaps in the formal education system. These reflections serve as informal diagnoses of the challenges in science teaching and offer a roadmap for improvement. Similarly, gaining insight into teachers' perspectives is essential not only for designing non-formal activities that effectively address the needs of educators and students but also for promoting stronger integration between formal and non-formal education. In this regard, some of the reviewed references indicate that students learn more and benefit more from non-formal education experiences when they are already familiar with the topics and content addressed, as their prior knowledge seems to condition the learning they can achieve (DeWitt and Storksdieck, 2008). Therefore, such integration between formal and non-formal opportunities can generate synergies that bridge the gap between these two domains, thus creating a seamless continuum of experiences that enriches science teaching and learning.

Furthermore, depending on factors such as teachers' personality traits or teaching styles, the same activity may serve a wide range of purposes, addressing both cognitive and affective goals, which are often interlinked rather than mutually exclusive. In this sense, considering these factors, the same non-formal education activity or context can serve different purposes depending on how it is developed, structured, sequenced, and connected with the work carried out in the classroom. In this context, it is the prioritisation of specific goals over others, rather than the initial establishment of certain objectives, that significantly influences the teachers' practice, the way they deal with the experience, and the overall outcomes of such activities (Karnezou et al., 2021). Nevertheless, even though teachers' agendas dominate the course and outcomes of non-formal experiences, there is always an element of unpredictability in learning in out-of-school environments (Uppin and Timoštšuk, 2022).

Finally, authors such as Garner et al. (2015) consider that it is also important that the students know exactly what is expected of them during the field trip. Nevertheless, they described how research shows that students are often unaware of the overall goals and thus they are unprepared for effective, goal-oriented learning during the activities. An implication of this is that teachers must therefore carefully inform their students about the goals pursued through participation, so that students can know what is expected of them during the activities.

Therefore, when researching within the framework of non-formal education, it is no longer sufficient to merely consider the general objectives of the activity proposed by the teacher, but also which ones are priorities for the teachers, in line with what this last author suggested. This is an aspect that we have not carried out throughout this study, but which would be interesting for future research to consider as a possible line of further investigation.

In conclusion, taking into account both the results of the systematic review and the perceptions shared by the teachers during the interviews conducted in the science clubs, it is evident that further analysis of teachers' perspectives within the specific framework of long-term activities is necessary, as a gap still exists in the literature given that far fewer studies focus on this type of activity.

In this way, we can come to understand the subtle differences that exist between short-term and long-term activities and be able to advise teachers in the best possible way regarding whether to opt for one, with what objectives or purposes, or to achieve what specific goals when choosing the other. It is clear that the characteristics and learning outcomes that can be derived from one and the other can be very different, and therefore, teachers approaching a short-term or long-term

activity with the same type of objectives, regardless of how it will be developed, could be a poor choice.

Therefore, it is necessary for us to know what benefits one provides, what achievements are attained, and what those of the other are, so we can better advise and support teachers when choosing what type of activity, they need to achieve their proposed goals, since they are the ones who truly control and know what they seek, what they need, and what options they should offer their students.

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Exploring Science Through Play: Assessing The Impact Of The PIXEL Board Game And Its Game-Based Learning Framework On Students' NOS Perception

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This study evaluates the educational potential of the board game PIXEL – Picture (of) the Universe, designed by the Italian National Institute for Astrophysics in collaboration with the Game Science Research Center. PIXEL, integrated within a Game-Based Learning framework, aims to enhance students' understanding of the Nature of Science, with a particular focus on the social and institutional dimensions of scientific research. The game's mechanics simulate astrophysics research, emphasizing collaboration, resource management, and inquiry associated with image resolution in astrophysics. Through gameplay and associated activities, students explored scientific processes in an engaging, risk-free environment. The study involved 32 high school students participating in a 40-hour program, which included gameplay, facilitation training, reflective diary writing, and feedback sessions. Using qualitative thematic analysis of students' diaries, the research identified significant shifts in perceptions of science and research. In the pre-activity, responses largely reflected formal, textbook-like views of science, emphasizing the scientific method as a rigid process. In the post-activity ones, students displayed a more nuanced understanding, highlighting collaboration, iterative research, and the human aspects of scientific inquiry and manifesting a personal point of view about science and researchers. The study confirmed PIXEL's effectiveness in promoting NOS understanding; it emphasized the importance of integrating games into well-designed educational frameworks, demonstrating the potential of GBL to help learners refine their ideas, increasing their complexity and aligning them more closely with the real practices of contemporary astrophysical research.

Keywords: Nature of Science, Game-Based Learning, Scientific Citizenship

Introduction

This study explores the educational potential of the board game PIXEL - Picture (of) the Universe (Figure 1), developed by the Italian National Institute for Astrophysics (INAF) in collaboration with the Game Science Research Center. PIXEL aims to promote understanding of the Nature of Science (NOS), particularly its social and institutional dimensions, through a Game-Based Learning (GBL) approach. By combining engaging gameplay with scientifically grounded content, PIXEL bridges students' experiences with the methodologies and dynamics of astrophysics research.

GBL is often used as an umbrella term for a wide range of educational practices that involve games. However, the mere use of games in educational settings does not, in itself, constitute GBL. A critical distinction concerns the role that the game plays in the learning process and, more specifically, the degree of agency afforded to learners.

Figure 1. PIXEL - Picture (of) the Universe; game set-up.



A first approach, which can be described as “game-as-tool” for learning, treats games primarily as vehicles for content delivery. In this case, disciplinary knowledge is embedded into gamified formats, such as quizzes or trivia-based games, with the main aim of increasing motivation or engagement. While these approaches may be effective forms of gamification, they do not fully align with the principles of Game-Based Learning, as gameplay remains largely instrumental and does not support deeper meaning-making processes.

A second approach conceptualizes the “game-as-model” of the expected learning outcomes. Here, game mechanics are intentionally designed to embody key processes, structures, or ideas in the domain of interest. Through interaction with the game system, learners can experience simplified or metaphorical representations of complex phenomena. In this case, GBL can occur when gameplay is accompanied by opportunities for reflection and sense-making, allowing learners to connect in-game actions with disciplinary concepts and practices.

A third perspective, which we refer to as “game-as-game”, positions the gameplay itself as the core learning practice. In this view, learning emerges from players’ autonomous decision-making, negotiation, and strategic action within the game system. Rather than serving as a means to transmit predefined or expected content, the game creates a space in which learners actively construct understanding through participation. From this perspective, the educational value of GBL depends strongly on the level of agency allowed by the game and on the role of facilitation in supporting reflection, discussion, and skills development. This perspective is often used in educational contexts to foster transversal competences, rather than focusing primarily on disciplinary learning.

PIXEL is intentionally designed to support both the game-as-model and the game-as-game perspectives. Its mechanics embody key features of scientific research, while gameplay itself constitutes a meaningful learning experience. When embedded within a structured Game-Based

Learning framework that includes facilitation and reflective practices, PIXEL enables students to explore and make sense of the Nature of Science not through explicit instruction, but through lived and negotiated experience.

Playfulness, Game Design And The Nature Of Science

Play is an inherent and universal aspect of learning across cultures and species, facilitating cognitive development, engagement, and social interaction (Huizinga, 1950; Smith, 2010). Neuroscience literature suggests that play activates brain regions involved in memory, problem-solving, and emotional regulation, fostering the foundations for lifelong learning (Puschmann et al., 2012). Grounded in these principles, PIXEL aims to create a meaningful and enjoyable learning experience that actively engages students in scientific practices and in reflecting on the Nature of Science.

PIXEL is a eurogame, a category of board games characterized by strategic mechanics and minimal reliance on chance. The game's central mechanic revolves around the resolution of astrophysical images, which represents the process of constructing detailed celestial images through observational data. During the observation phase, players must place tiles of different sizes that represent portions of the observed object at incremental resolutions. Players must use resources strategically to improve telescopes, to conduct observations, and to build an image collaboratively. The mechanics emphasize:

1. Iterative research. Lower-resolution tiles are larger and require fewer actions, mirroring the preliminary surveys astrophysicists conduct before focusing on detailed observations.
2. Collaboration and competition. Observational data is shared among players, representing the collaborative nature of scientific research, while maintaining competitive gameplay, representing competition in academia.
3. Scientific practices and professionalism. Winning the game requires players to build a coherent strategy, allocating limited resources to publications, facility improvements, staff growth, and multidisciplinary specialisation, thus reflecting the constraints and trade-offs of real-world scientific research.

PIXEL was designed to embody NOS principles, i.e., the values, practices and social dimensions of scientific knowledge. Among the different approaches addressing it, we chose to use the Reconceptualized Family Resemblance Approach (RFN), which encompasses both cognitive-epistemic and social-institutional aspects of science (Erduran & Dagher, 2014). These include practices, knowledge generation, social organization, and the reward systems of science. A key focus was to present scientific work as a human endeavour, offering students a holistic view of how research communities operate. The study evaluated PIXEL's educational impact through two research questions:

1. Can PIXEL, within a GBL experience, enhance students' understanding of the social and institutional dimensions of research in astrophysics and beyond?
2. Can this GBL experience foster a more personal and humanized perception of researchers and the research process?

Educational Design And Research Methodology

The study follows a qualitative case study design, aiming to validate the educational potential of PIXEL - Picture (of) the Universe in fostering students' understanding of the social and institutional dimensions of science. The board game was implemented within a structured GBL

intervention carried out in the context of the Italian PCTO (Pathways for Transversal Skills and Orientation) non-formal program, a national initiative for Italian high school students that requires them to complete a set number of hours of learning in collaboration with external educational or professional partners, in order to achieve a broader educational experience that extends beyond formal learning.

The 40-hour educational program – distributed over 5 to 6 months depending on the local schools – took place in 5 Italian cities and allowed participants to experience the game in multiple roles (as players, facilitators, and reflective learners). The intervention combined gameplay, structured debriefing, and reflective writing to promote NOS understanding. The design explicitly avoided direct instruction about NOS concepts or the social dimensions of science, so that any conceptual change could be attributed to the students' experience with the GBL process itself. Voluntary participation was emphasized to align with the principle of play as a voluntary attempt, fostering genuine engagement and motivation. In the following, we outline the structure of the educational design.

1. Training sessions. Students were introduced to basic GBL principles, to PIXEL's mechanics, and the scientific concepts underpinning the game, such as astrophysical image resolution. Importantly, social and institutional aspects of NOS were not explicitly addressed, allowing these to emerge organically during gameplay and debriefing.
2. Facilitation practice. Students practiced facilitating PIXEL sessions with peers, learning to guide gameplay and conduct debriefs, which are critical for metacognitive learning. To support this, a graphic debrief tool was provided to help analyse player interactions and themes.
3. Reflective diaries. Between interventions, students documented their experiences and reflections by answering open-ended questions in diaries, which served as key data sources for the study. This reflective practice aimed to enhance critical thinking and self-regulated learning.
4. Feedback sessions. Participants engaged with astrophysicists and game creators in two feedback sessions, discussing their progress, challenges, and insights, further deepening their understanding of the research world.

Qualitative Data Collection And Analysis

To explore students' evolving conceptions of science, data were collected through reflective diaries compiled after each session. The diary method was chosen to support a metacognitive, explicit-reflective approach to learning about NOS (Lederman et al., 2002; Abd-El-Khalick & Lederman, 2023). Each diary included 3-5 open-ended questions encouraging students to articulate their views on science, research, and scientists. The first and last sessions contained identical questions – "What is science to you?", "How does scientific research work?", and "How do researchers work?" – allowing for a pre/post comparison of conceptual change. For the purposes of this study, only these sessions are presented in the following sections, as the others were used to track students' progress in understanding and facilitating the game. This qualitative and reflective approach aligns with action research traditions (Lewin, 1948; Cunningham, 1976), in which the act of observation can itself promote transformation. In this sense, reflective diaries were both a learning tool and a data source.

We conducted two complementary analyses: a content-oriented analysis, focused on identifying recurring themes in students' reflection diaries, and an expressive register analysis, aimed at capturing shifts in students' style and tone.

The content-oriented analysis was inspired by the Reflexive Thematic Analysis framework (Braun & Clarke, 2006, 2019). We adopted a primarily inductive approach, allowing themes to emerge from the diaries while remaining attentive to our research questions. The analysis was conducted mainly at a semantic level, focusing on the explicit content of students' writings, though in some cases we drew on latent interpretations. Ten researchers, organised into five pairs, independently coded the data. Each pair identified emerging themes and assigned preliminary keywords to each data entry. A longitudinal perspective was then applied to trace the evolution of themes for each participant. Following these initial cycles, the groups compared results, synthesized the outcomes, and refined them through iterative discussions until a stable pool of themes was established. This process was iterative, involving multiple cycles of code creation, evaluation, and refinement.

In the analysis, we noted significant variation in the tone and style of student responses, ranging from formal, stereotypical formulations to more personal, elaborated accounts. To account for this, we also categorised entries into expressive registers using a latent thematic analysis. Well-structured and elaborate responses were coded either as bookish responses or personal elaboration, whereas superficial, incomplete, or nonsensical entries were tagged separately. This additional analysis provided insight into shifts in students' expressive registers, highlighting a move from bookish, stereotypical formulations to more personal, reflective engagements with science, research, and the role of scientists.

For each question of the first and last sessions, the number of occurrences of each tag was counted across the entire sample to determine how often specific themes were mentioned. The percentage frequency normalized over the number of tags in the pre (45, 35, 45 tags for each question, respectively) and in the post (56, 81, 54) was then calculated.

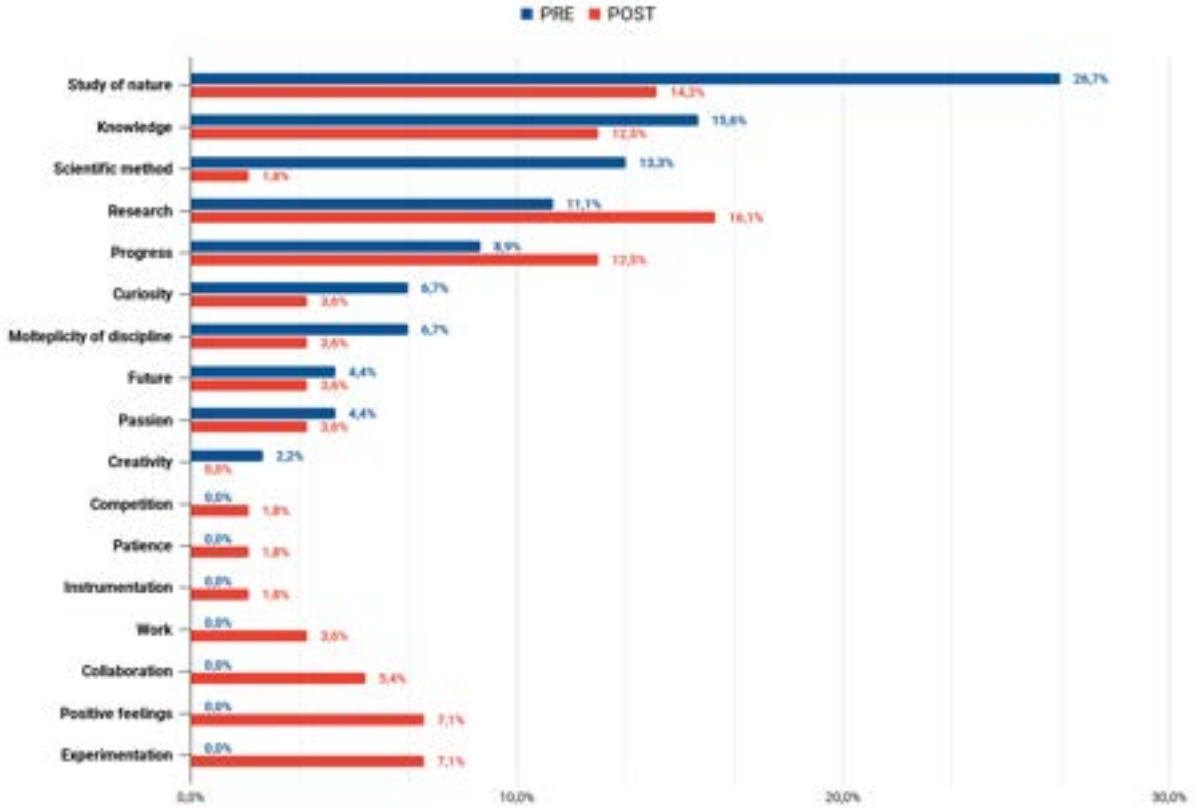
Finally, the tags were grouped within the two systems of the RFN: the cognitive-epistemic and the social-institutional systems.

Results

The findings presented hereafter highlight notable changes in students' perceptions, emphasizing a broader and more nuanced understanding of science and research. The results are introduced by discussing the three questions separately.

Perceptions of Science. Students' responses to the question, *"What is science for you?"*, initially clustered around ten themes, such as **Study of nature**, **Knowledge**, **Scientific method**, and **Research**. By the end, these expanded to 16 themes, reflecting a richer and more diverse understanding. Significant reductions occurred in the themes **Scientific method** (from 6 to 1 occurrences, -11.5%) and **Study of nature** (from 12 to 8, -12.4%), indicating a shift away from narrowly defining science through traditional concepts. Meanwhile, themes such as **Progress** (from 4 to 7, +3.6%) and **Research** (from 5 to 9, +5.0%) grew in prominence, alongside new themes like **Collaboration** (0 to 3, +5.4%), **Experimentation** (0 to 4, +7.1%) and **Positive feelings** (0 to 4, +7.1%), a theme we introduced to count the entries with an explicit sense of positive values associated to science. See the graphic of Figure 2 for the percentage frequency of each theme. These changes suggest that students began to view science as a multifaceted and collaborative endeavour, emphasising discovery and shared passion.

Figure 2. Frequencies of the themes emerged in the answers to the question "What is science for you?" asked at the beginning of the project (blue, pre) and at the end (red, post)



Understanding Scientific Research. The students' understanding of scientific research evolved from 7 themes in the pre-activity phase to 18 themes post-activity, as shown in Figure 3. The theme **Scientific method** dropped dramatically (from 25 to 8 occurrences, -61.5%), while new concepts, such as **Astronomical observation** (from 0 to 6, +7.4%), **Commitment** (0 to 7, +8.6%), emerged, often influenced by the game's design. For example, themes such as **Objectives** (0 to 8, +8.9%) and **Instrumentation** (0 to 5, +6.2%) can be traced back to the game mechanics, where players simulate research goals and resource management. The theme **Replicability**, which disappeared entirely (from 3 to 0, -8.6%), was deemed less relevant in the context of astrophysics, a field where transient and non-replicable phenomena are common. This shift illustrates the "efficiency" of GBL approach to reshape students' perceptions, broadening their understanding of the complexity and human dimensions of research, and in this case, wiping out a concept.

Perceptions of Researchers' Work. Responses to the question, *"How do researchers work?"*, also showed significant variations from pre- and post-activities (Figure 4). The **Scientific method** theme declined significantly (from 12 to 5 occurrences, -17.4%), while themes like **Collaboration** (from 5 to 12, +11.1%) and **Objectives** (0 to 10, +18.5%) grew substantially. The reduced focus on **Objectivity** (from 8 to 1, -15.9%) underscores the game's emphasis on the subjective, strategic, and collaborative aspects of research, challenging the perception of science as purely objective. Students began to view researchers as individuals navigating complex goals and balancing cooperation and competition, an insight that aligns with the educational objectives of the game.

Figure 3. Frequencies of the themes emerged in the answers to the question "How does scientific research work?" at the beginning of the project (blue, pre) and at the end (red, post)

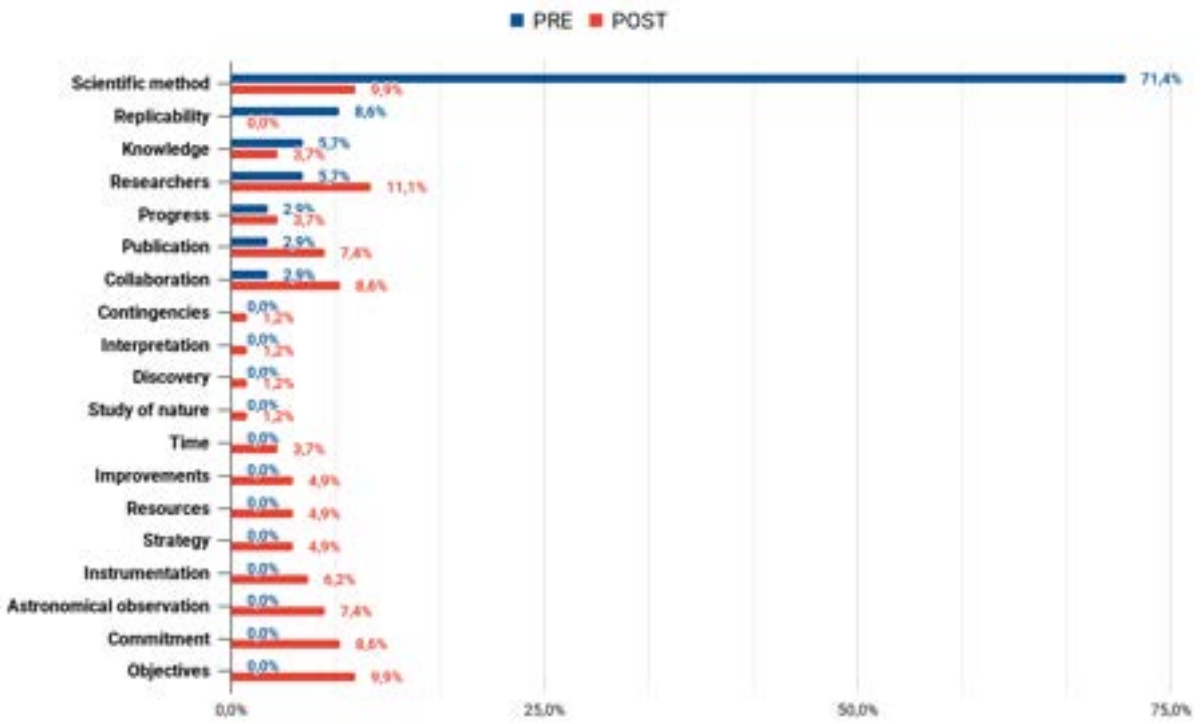
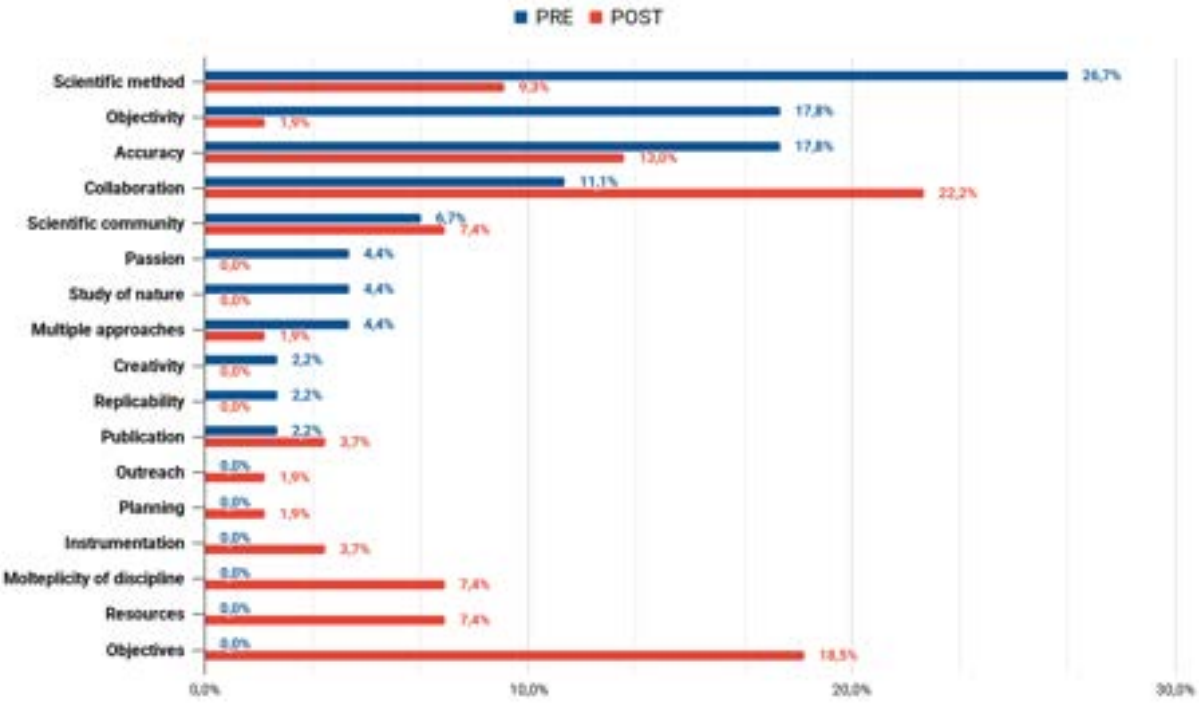
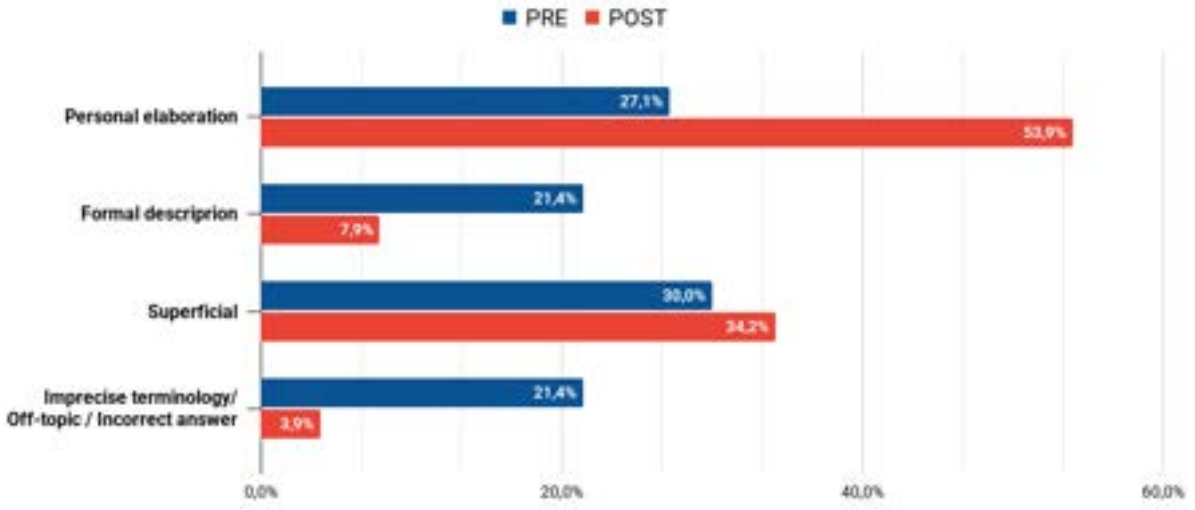


Figure 4. Frequencies of the themes emerged in the answers to the question "How do researchers work?" at the beginning of the project (blue, pre) and at the end (red, post)



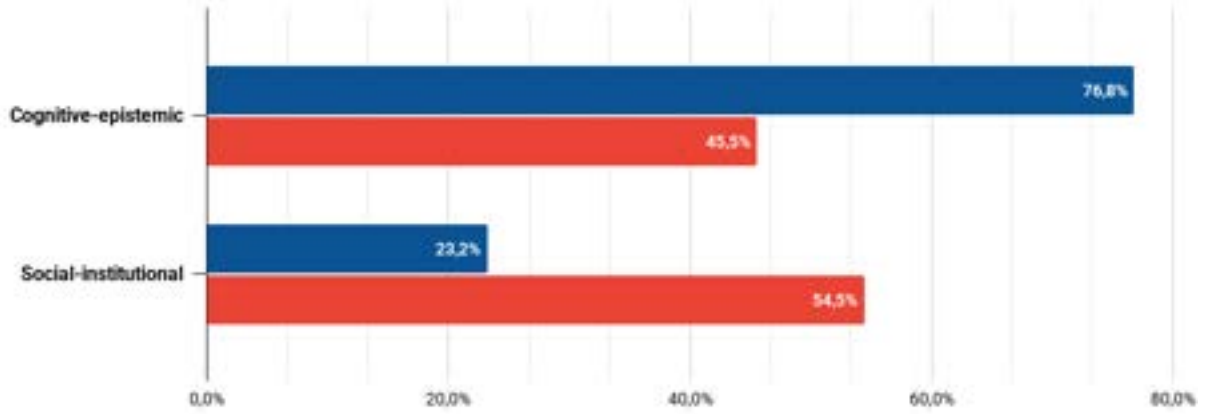
Modal Analysis. A comparative analysis (Figure 5) of response categories revealed a major shift from formal, textbook-like answers to personal elaborations, which increased by 26.8% (from 19 to 41 occurrences). Conversely, formal descriptions decreased by 13.5% (from 15 to 6). This transition reflects a deeper engagement with science, as students moved beyond memorized knowledge to expressing their own perspectives, enriched by the GBL experience. Incorrect or off-topic responses nearly disappeared, highlighting the game's effectiveness in fostering comprehension.

Figure 5. Tag for modal analysis for the three questions (pre-blue and post-red)



RFN mapping. To further examine how the GBL experience influenced students' understanding of the Nature of Science, the themes emerging from their responses were interpreted through the lens of the Reconceptualized Family Resemblance framework. Specifically, each theme was associated with either the cognitive-epistemic or the social-institutional system, and their relative presence was compared across the pre- and post-intervention phases. The resulting distribution is illustrated in Figure 6.

Figure 6. Frequency of the themes addressing the two RFN systems (pre-blue and post-red)



Before the intervention, students' representations of science were largely dominated by themes related to the cognitive-epistemic system, which accounted for 76.8% of all coded occurrences. After the GBL experience, this proportion decreased substantially to 45.5%. In contrast, themes associated with the social-institutional system increased markedly, from 23.2% in the pre-phase to 54.5% in the post-phase.

This redistribution highlights a significant shift in how students conceptualized science. While their initial views emphasized methods and procedural aspects, their later reflections increasingly foregrounded the human, social, and institutional dimensions of scientific work. Such a reorientation suggests that the GBL experience supported a more balanced and comprehensive understanding of science, in line with the integrated view of scientific practice articulated by the RFN framework.

Discussion and Conclusions: Games as an activator for NOS reflection

This study explored the educational potential of the board game PIXEL – Picture (of) the Universe when embedded within a structured GBL framework, with particular attention to

students' understanding of the NOS. Rather than focusing on the effectiveness of the game as an isolated artefact, the analysis highlights how the interplay between game design, educational orchestration, and reflective practices can foster more informed, nuanced and humanized views of scientific research.

The findings indicate a clear shift in students' perceptions of science and scientific research, particularly regarding the social and institutional dimensions of NOS. Prior to the intervention, students' responses largely reflected formal, textbook-like conceptions of science, often centred on the scientific method as a linear, rigid procedure. Such views are well documented in the literature and remain a persistent challenge in science education (Abd-El-Khalick & Lederman, 2023). Following the GBL experience, students' reflections became more diversified, articulated, and personal. The increased salience of socio-institutional themes suggests that students began to perceive science as a collective, situated human enterprise rather than an individual, abstract, and decontextualised process. This transformation aligns with previous studies (Buaraphan, 2012; Erduran et al., 2019), positioning GBL as a viable learning strategy for making epistemic and social processes of science visible and discussable. Importantly, these outcomes cannot be attributed solely to the game. As argued by Clark (1994), learning does not reside in the medium itself but in the instructional methods through which it is enacted. In this sense, PIXEL functioned as an epistemic artefact whose educational value emerged through its integration within a carefully designed GBL pathway.

Moreover, this study shows how specific game mechanics can be systematically mapped onto NOS dimensions through the Reconceptualized Family Resemblance Approach, effectively linking game design, gameplay dynamics, and students' reflections. Mechanics such as competing objectives and collective construction made core scientific practices experientially accessible, highlighting tensions between collaboration and competition, uncertainty and decision-making. The findings suggest that the effectiveness of GBL for NOS lies in the coherent alignment of game mechanics, facilitation, and reflective practices, fostering authentic and experience-based understandings of science.

Indeed, the results highlight a shift in students' expressive registers from formal descriptions to personal elaborations, indicating not only conceptual change but also increased agency and epistemic engagement with science. Reflective diaries played a key role in supporting this transformation, enabling students to connect their gameplay experiences with broader perspectives on scientific research and to develop a more confident, personal scientific voice.

In conclusion, the findings underline the potential of analogue board games as effective tools for addressing the epistemic and social dimensions of science, while emphasising that the impact of GBL depends on thoughtful educational design rather than on games as stand-alone solutions. For educational practice, this highlights the need for intentional facilitation, debriefing, and reflection, pointing to the importance of teacher education programs that frame GBL as a comprehensive pedagogical approach.

On the other hand, as a qualitative case study involving a small, self-selected group of students, the findings are not intended to be generalised statistically. While the study is situated within the specific domain of astrophysics, this choice represents a strength rather than a limitation. Astronomy is widely recognised as a "gateway science" (Salimpour et al., 2021), capable of engaging learners and fostering broader reflections on science as a human and epistemic enterprise that extends beyond the disciplinary context.

Overall, this study contributes to ongoing discussions within the ESERA community about how playful and experiential approaches can support learning about the Nature of Science. By

combining game design, the RFN framework, and reflective educational practices, the PIXEL GBL experience offers an example of how games can be used not merely to motivate learners but to foster deeper epistemic understanding and personal engagement with science.

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Complexity-Differentiated Learning To Support Students' Lab Work In Out-Of-School Student Laboratories

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Out-of-school student laboratories (OSL) are often hosted by institutions of higher education like universities and aim to facilitate interest in science. A key component of these learning offers is the hands-on experience which for STEM-subjects mainly means conducting experiments. While research has shown that OSL are able to foster situational interest and knowledge acquisition, the effects are rather small and in general do not last over a longer period of time. The integration of digital media and the provision of complexity-differentiated tasks could help promote motivation and aid knowledge acquisition while still staying true to the hands-on approach of the OSL. Therefore, a new method for digital and complexity-differentiated learning in the OSL was developed, implemented and tested. Our recent study focused on the investigation of complexity-differentiation while using this method for lab work in the OSL. One group used complexity-differentiated material based on a differentiation matrix (DM), while the other group was not aware of the complexity-differentiation in the material and conducted station learning (SL). The study was conducted with thirteen 8th grade classes (N=280), evaluating the influence on emotions, expectancy value motivation and knowledge acquisition. In addition, the choice of fields or stations was recorded. The results will be presented in this proposal and possible consequences for the use of likewise methods in the OSL will be shown.

Keywords: out-of-school student laboratories, digital advances, differentiation

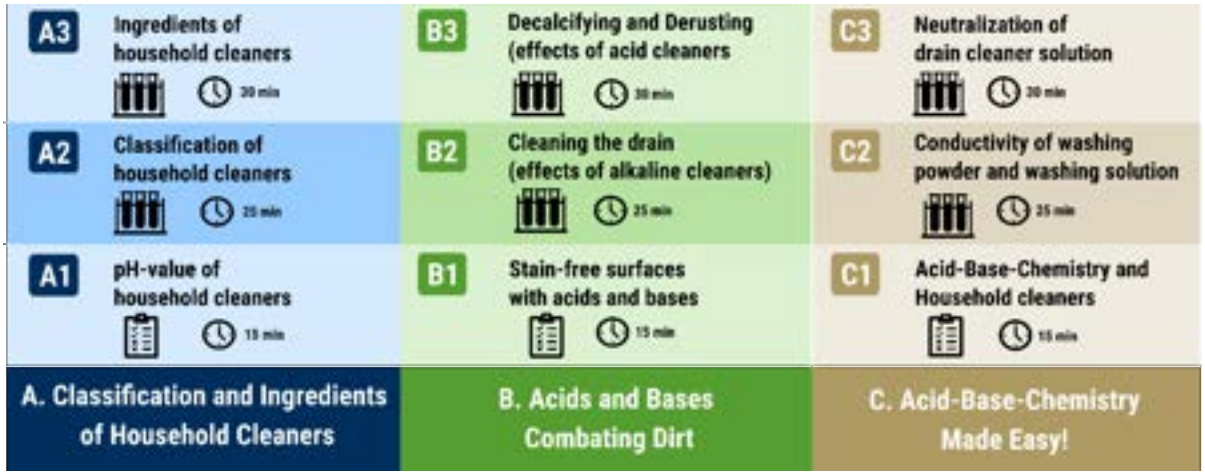
Introduction

Promoting interest in natural sciences is a primary goal of out-of-school student laboratories (OSL). By offering a stimulating and research-related program they aim to motivate students to engage with scientific content and pursue a career in STEM (Stamer et al., 2020). However, empirical studies on the promotion of interest in OSLs often show only short-term effects (Lewalter et al., 2021). One way to improve the effectiveness of OSL might be adapting the courses to different levels of complexity to appeal to more participants (Affeldt et al., 2015). This could be supported by using digital media while thereby increasing motivation and learning outcomes (Hillmayr et al., 2020). The following contribution presents a study that tests the effectiveness of a new method in the OSL combining these approaches: the use of digital and complexity-differentiated learning modules (DCDLM).

Theoretical Foundations

The basis of DCDLMs is a differentiation matrix (Sasse & Schulzeck, 2021), in which tasks are created according to thematic complexity in a horizontal direction and tasks according to cognitive complexity in a vertical direction. The supposedly easiest field is therefore at the bottom left of the matrix, the supposedly most difficult field at the top right. For our OSL we use a 3x3 matrix. In previous tests, this size has proven to be particularly suitable for a three-hour student lab, as a large part of the learning module can be viewed and worked on by students at this time (ter Horst et al., 2024). Two different types of tasks are used: experimental and theoretical fields (see Fig.1).

Figure 1. Differentiation matrix for the exemplary module "household detergents".



Multitouch Learning Books (Huwer et al., 2018) are used for our DCDLMs, which contain the differentiation matrix and the material used per field. The learning environment was designed according to principles of the Cognitive Theory of Multimedia Learning (Mayer & Fiorella, 2014) with the aim of minimising the extraneous cognitive load (Sweller et al., 2011). Learners receive feedback by comparing their answers with solutions and can determine their own approach in terms of content and time (Moreno & Mayer, 2007).

Theoretical Proposals

In addition to the implicit effects of the differentiation (e.g., learning aids) and digitalisation measures used (e.g., tablet as a learning companion), DCDLMs' primary intended effect is through transparent complexity differentiation. This enables students to make an initial assessment of the complexity of the task and, if desired, to adapt it to their self-perceived level of knowledge (Corbalan et al., 2011). The differentiation matrix also gives them an overview of all the tasks in the course, which can help them to bring structure to the topic. This should provide additional clues for the decision in favour of or against a task, potentially leading to better choices (Relan, 1995). By comparing them with solutions, they also receive feedback on their level of knowledge and can then adjust their learning path (Bennett, 2011). To analyse the effectiveness of the method, an exemplary module on the topic household detergents was evaluated.

Aims Of The Study

This study focuses on the complexity-differentiation of the DCDLMs and its potential effectiveness. Therefore, a distinction was made between two settings: one in which the learners are aware of the complexity- differentiation of the learning module (dDM) and one in which they were not (dSL). In a pre-post quasi-experiment, the effects of the learning design on emotions (joy, curiosity, boredom, frustration), expectancy value motivation (expectation of success, utility value) and influences on performance (subject-specific and topic-specific knowledge) were investigated, since we expected emotional-motivational and cognitive benefits from the described learning design. Finally, the choice of fields was exploratively analysed to draw conclusions about possible connections.

Hypothesis 1 (emotions): Both intervention groups show an increase in joy and curiosity (cur) from pre- to post-test and a decrease in boredom (bor) and frustration (fru). The intervention group dDM shows more positive changes in enjoyment and curiosity and more negative changes in boredom and frustration compared to the intervention group dSL.

Hypothesis 2 (expectancy value motivation): Both intervention groups show an increase in expectancy of success (ex) as well as utility value (uv) from pre- to post-test. The intervention group dDM shows a more positive change compared to the intervention group dSL.

Hypothesis 3 (performance): Performance increases in terms of subject-specific (ssk) and topic-specific knowledge (tsk) in both intervention groups. Compared to the dSL intervention group, the dDM intervention group shows a higher increase in knowledge from the pre-test to the post-test.

Research question: How does the choice of fields differ between the two intervention groups (dDM, dSL)?

Method

The study was conducted with thirteen school classes from five schools in Thuringia (N=280) from May to June 2023. In the following, for hypotheses H1-H3 (a), the results for changes across the student lab day are first reported using t-tests for dependent samples. Two complementary statistical methods were then used to test whether the changes in the groups differed from each other (H1-H3): (b) In the change score approach, the difference between pre- and post-scores (post minus pre) is predicted by group membership in a multiple regression (dDM=0 vs. dSL=1). (c) In the ANCOVA approach, the post-test value is predicted by the pre-test value and the group membership (dDM=0 vs. dSL=1). Parametric tests are used due to the respective group size. Table 1 lists the results for (a), (b) and (c). Finally, descriptive comparisons for the research question on field selection are presented.

Results

Looking at emotions, there was a significant increase in enjoyment and a decrease in boredom and frustration across both groups (a). However, the decrease in negative emotions was only significant for the dSL intervention group. Curiosity also only increased significantly in the dSL intervention group. Contrary to our hypothesis, the results for the direct group comparisons (b, c) consistently showed a significantly greater increase in curiosity in the dSL group.

When looking at expectancy value motivation, there was an increase in the expectation of success across both intervention groups, which was also significant for both. Contrary to our hypothesis, a significant decrease in utility value was observed across both groups, although this was only significant for the dDM intervention group (a). The results for the direct group comparisons (b, c) consistently showed, also contrary to our hypothesis, a significantly greater decrease in utility value in the dDM group.

The development of knowledge regarding acid-base chemistry (ssk) showed that it increased significantly both across both intervention groups and for each individual group. There was a significant increase in the development of knowledge regarding household detergents (tsk) across both intervention groups, although this was only significant for the dDM intervention group (a). The results for the direct group comparisons (analyses b and c) showed no group differences.

Differences between the two groups can also be described in the choice of fields. The number of fields selected in the dDM group is clearly shifted towards the easier fields. The choice of fields in the dSL group is more evenly distributed and shows a significantly higher proportion of the more difficult fields (Fig. 2).

Table 1. Results of analysis a), b) and c).

	a) t-tests								
construct	**overall**			**dDM**			**dSL**		
	t	*p*	*d*	*t*	*p*	*d*	*t*	*p*	*d*
Emotions (H1)									
Joy	4,37	**0,001**	0,28	2,06	**0,042**	*0,19*	4,9	**0,001**	0,4
Cur	1,14	0,256	0,06	-1,18	0,24	0,09	3,7	**0,001**	0,27
Fru	-2,08	**0,039**	0,13	-1,07	0,143	0,09	-2,03	**0,045**	0,18
Bor	-2,58	**0,01**	0,16	-1,23	0,221	0,11	-2,74	**0,007**	0,23
Expectancy value motivation (H2)									
Ex	5,59	**0,001**	0,5	3,67	**0,001**	0,32	4,6	**0,001**	0,38
Uv	-4,01	**0,001**	0,22	-4,87	**0,001**	0,32	-0,55	0,582	0,05
Performance (H3)									
Ssk	4,39	**0,001**	0,24	3,2	**0,002**	0,2	3,01	**0,003**	0,31
Tsk	3,29	**0,001**	0,26	3,07	**0,002**	0,32	1,39	0,169	0,16

construct	**b) Change-Score**		**c) ANCOVA**	
	β	*p*	*β*	*p*
Emotions (H1)				
Joy	0,104	0,088	0,04	0,491
Cur	0,183	**0,003**	0,12	**0,014**
Fru	-0,046	0,452	-0,004	0,934
Bor	-0,095	0,12	-0,02	0,716
Expectancy value motivation (H2)				
Ex	0,033	0,593	-0,034	0,523
Uv	0,136	**0,027**	0,101	**0,036**
Performance (H3)				
Ssk	0,067	0,288	-0,009	0,861
Tsk	-0,065	0,309	-0,087	0,158

Figure 2. Choice of fields for the dDM (right) and dSL group (left).



Discussion And Implications

The aim of the study was to test the complexity-differentiation of DCDLMs in the OSL for two varying settings. Despite positive results across both groups, the dSL group showed advantages over the dDM group, which is contrary to the hypotheses formulated at the beginning. The different field selection of the groups may offer an initial explanation for this.

The dSL group appears to benefit from the diversified choice of fields of varying complexity showing both affective and cognitive advantages. This may be due to a more interest-driven approach. Knowledge of the varying difficulty of the fields therefore seems to have a negative effect on the participants in the dDM group, as they generally choose unhelpful learning strategies (easier fields).

The reasons for this can be manifold: these include the reduction of effort costs (Flake et al., 2015), inadequate self-evaluations of the level of performance (e.g. due to a low ability self-concept) or difficulties in self-regulation, if the intention was to take the complexity into account. In the discussion at the conference the possibility of a higher cognitive load for the students with the new method was also discussed, due to their unfamiliarity with it.

Thus, there is a need to improve the choice of fields. More specifications could be made to encourage or obligate the students to include more difficult fields. Also, a more precise diagnosis of the level of knowledge could be made at the beginning. As positive results can be found in both intervention groups, the use of DCDLMs in the OSL appears to be potentially useful but requires adjustments to offer advantages over previous didactic concepts.

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How Citizen Science Can Support Teachers And Students In Engaging With Scientific Research: The Citizen Science School Rome Technopole

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Citizen Science can represent an informal and engaging learning method for both students and teachers to explore scientific research. At INFN Frascati National Laboratory we organized, in collaboration with European Citizen Science Association (ECSA), the European Citizen Science Academy and Citizen Science Italia, a Citizen Science School addressed to high school students, teachers, University students and researchers focused on Rome Technopole's research macro areas. The School allowed participants to work on real research projects that provided concrete results and fostered collaborative reflections on the usage of citizen science as an educational strategy.

Keywords: Citizen Science, STEM education, Project-based learning

Introduction

Informal and non-formal learning experiences have been shown to exert a highly positive impact on students, particularly in the context of STEM subjects (Hussim et al. 2024). While formal learning is a well-structured activity within educational institutions, informal learning takes place outside the school environment (Ayar, 2015) and provides unique opportunities to all learners because of the flexibility and ease of access to learning specific knowledge or skills (Jenson et al., 2023). This is even more true for Project-Based Learning (PjBL), where students experience and indulge in complex, real-world tasks, resulting in an idea, a product, or prototypes (Santhosh et al., 2023).

In this context, citizen science approach could represent a very valid ally. Although citizen science (CS) encompasses a wide range of activities and practices (Haklay et al., 2020), making it difficult to define it broadly (Haklay et al., 2021), it can be delineated as the involvement at various levels of the public in scientific investigation and data collection (SEEDS project, 2025) that has a genuine scientific outcome, such as new knowledge, conservation actions, or policy changes (ECSA, 2025a). CS is in fact a way of doing scientific research, that revolutionize the relationship between scientific community and citizens and responds to an Open Science approach, indicated as a priority by the European Commission (European Commission, 2025); in Italy, it has recently become an integral part of the National Plan for Open Science (MUR, 2025) of the National Research Program (PNR) 2021-2027 of the Italian Ministry of University and Research. In addition, CS has great potential for schools. By its very nature, it is perfectly in line with a Project-Based Learning, as it facilitates students' active participation and strengthens the connection between scientific exploration and their personal experiences; in addition, its

methodology enhances critical thinking and experiential learning of the scientific method, while establishing meaningful ties with the research community through tangible projects. CS is also beneficial for teachers, who take a more engaged and rewarding role, moving away from the conventional model of knowledge transmission, and emerging as key drivers of change towards a contemporary and dynamic educational community (SEEDS project, 2025b)

For all these reasons, at INFN Frascati National Laboratory we decided to propose a citizen science initiative among the activities carried out by Rome Technopole project: a Citizen Science School addressed to high school students and teachers, university students and researchers. The school was designed to provide first-hand experience of citizen science, through the step-by-step development of real scientific research projects that exploit this methodology.

Methodology

Context And Setting

The Citizen Science School1 was organized at INFN Frascati National Laboratory within the Rome Technopole2 innovation ecosystem in collaboration with the European Citizen Science Association (ECSA), the European Citizen Science Academy and Citizen Science Italia (CSI).

As the largest Italian research center devoted to nuclear and subnuclear physics with accelerators and related applications, the Laboratory proved to be an ideal setting for the School. Its environment allowed participants to engage directly with a cutting-edge research hub that integrates a broad spectrum of disciplines—ranging from particle and theoretical physics to technological development and computational studies—and brings together professionals from both STEM and non-STEM backgrounds. Furthermore, the School drew significant advantage from the Laboratory's long-standing experience and recognized expertise in organizing educational and outreach initiatives aimed at schools and the broader public (Bertelli et al., 2023). The presence of dedicated rooms and facilities further contributed to creating an effective and welcoming learning atmosphere.

Rome Technopole is the Ecosystem of Innovation of Rome and the Lazio region, in central Italy, built among the NextGenerationEU plan and composed of territorial leaders of research and innovation and organized in a network of state and private universities, public research organizations, local authorities, highly qualified and internationally recognized private companies. Overall, it consists of 39 Founder Partners: 7 Universities in Lazio, 4 National Research Centers based in Lazio (CNR, ENEA, ISS, INFN), 2 small and medium-sized enterprises, 17 large companies and multinationals, 3 local institutions (Lazio Region, Municipality of Rome, Lazio Chambers of Commerce), 2 business associations that are members of Confindustria and INAIL, a nonprofit public entity. The core of the project is developed on three thematic areas: Energy Transition, Digital Transition and Health & Bio-Pharma.

Two additional organizations played a crucial role in the design and implementation of the School: the European Citizen Science Association (ECSA), whose primary objective is to support public participation in research across the natural sciences, social sciences, humanities, and the arts, and Citizen Science Italia (CSI), which is committed to ensuring that citizen science is recognized, promoted, and adequately funded and operates in Italy. Both organizations contributed with their expertise and experience in the field of citizen science to the realization of the School.

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[1] https://comedu.lnf.infn.it/citizen-science-school-rome-technopole-2025/

[2] https://www.rometechnopole.it/en/

Participants And Research Groups

The School was addressed to a mixed group of 25 people including high school students (16 years and older, attending the last two years of high school) and teachers from across Europe, university students from European universities, and researchers from Rome Technopole. The choice to target a diverse audience was mainly motivated by the need to simulate as realistically as possible the real case scenario of the citizen science approach, but also by the aim of testing our innovative educational approach with schools and, at the same time, evaluating its effect on scientific community. Participants were randomly selected among those who had applied for registration, considering gender balance and geographical diversity. In total, we involved 20 non-experts participants from 4 different countries (Finland, Italy, Serbia, Turkey): 5 teachers, 8 university students and 7 high school students. These participants were then joined by 5 Italian researchers from the Rome Technopole project, engaged through an open call to all Rome Technopole organization, and 5 citizen science experts of ECSA and CSI who acted as facilitators. During the School, participants worked in 5 groups of 4 people each, comprising at least one university student, one teacher and one high school student, plus researchers. Each group worked separately on a research topic.

The School's Research Projects

Since one of the fundamental ideas behind the School was to provide participants with direct, practical involvement in citizen science, we chose to engage them in authentic, ongoing scientific projects. The selection of research topics was determined by researchers from the Rome Technopole who participated in the initiative, as they corresponded to the main projects they were currently working on. Given the breadth and multidisciplinary nature of the Rome Technopole project, the final research themes were highly diverse and included: Antibiotic resistance; VR/AR/MR environments; Dentistry; Digital and physical spaces in prisons; Physics, energy, and sustainability.

Once the research areas had been defined, the second—and most delicate—phase in the School's design was devoted to addressing these topics through a citizen science approach. To this end, the researchers were invited to reflect, with the support of citizen science experts, on which elements of their studies could benefit from citizen involvement. They were asked to consider whether there were data or observations that citizens could provide, whether citizens might help extend the project's impact or disseminate it within their communities, but also, more broadly, how collaboration with the public could enrich their research perspectives.

Subsequently, the researchers began to outline a preliminary draft of a research program to be carried out during the School. It is important to emphasize that, unlike other outreach activities to which they had previously contributed, they were not asked to define what the participants *should do*. Instead, they were invited to identify the areas in which participants could *meaningfully contribute*—without specifying the activities to be carried out in a prescriptive manner. The intent was to leave ample room for participants to contribute not only to defining the research results, but also to the methodological approach.

The Realization Of The School

The Citizen Science School Rome Technopole was held from February 3 to 7, 2025, with activities running from 9:30 am to 6:00 pm. Given the School's ambition to design and set in motion five citizen science projects within this limited timeframe, the introductory phase was deliberately kept concise: it consisted of a brief overview of citizen science and of the five research areas. Then, the working groups were formed, based on participants' preferences, if any. From that moment on, the groups continued their work independently during parallel sessions,

except for two scheduled plenary meetings held each day—one in the morning and one at the end of the day—to review the progress made, exchange reflections, and share emerging ideas, challenges, and experiences. As the days progressed and collective discussions unfolded, it became increasingly evident that the groups were encountering similar difficulties, regardless of their specific research focus. For example, all teams faced challenges in formulating their research question(s) and in defining an appropriate methodology to achieve their objectives. Equally clearly, it became apparent that these issues could be addressed with common solutions or approaches. Another aspect that emerged was that, just like in a real citizen science project, throughout the course of the School, all the actors involved were making different contributions and adopting different stances based on their individual needs, availability, personal dispositions, often stepping outside their typical professional role. Some teachers adopted a more passive role, allowing themselves to be guided; some students assumed leadership responsibilities and organized the work as if they were instructors; and some researchers collaborated closely with the groups, working alongside them throughout the activities and sometimes leaving their role as experts behind.

The final day of the week was devoted to the presentation of project outcomes by all groups, followed by a concluding discussion with the citizen science experts, who identified both the strengths of the work accomplished and areas with potential for further improvement. Each group succeeded in developing innovative strategies to initiate or enhance citizen engagement within their respective research contexts. In some cases, the proposed approaches focused on raising public awareness of specific issues or on collecting data of value to the researchers; in others, the groups formulated practical plans to guide the future evolution of their projects. In two cases, groups also managed to pilot their proposals with a small cohort of acquaintances, providing an initial test of feasibility.

Results

The specific outcomes achieved by each research group are presented in detail below, together with a brief description of the methodology used.

Research Line 1: Antibiotic Resistance

Lead Researcher: Silvia Cammarone, Department of Chemistry and Technologies of Drug, Sapienza University of Rome.

Aim. Raise public awareness and promote responsible antibiotic use by assessing citizens' knowledge, habits, and risk perceptions, and by creating pathways for sustained engagement.

Process and products. The group initially developed a survey aimed at evaluating citizens' knowledge of antibiotics and their use, as well as exploring their perceptions of the issue from both individual and collective perspectives. Then, the team expanded its vision into a larger engagement concept, "IGEA" (cItizen enGagement awarEness on Antibiotics) that included educational programs in schools, online seminars on correct antibiotic use, interactive games for children and a monitoring app concept that should allow users to record cases of infections, antibiotic use, and perceived treatment effectiveness, as well as send water samples to nearby laboratories to check for bacterial contamination.

Research Line 2: User Interfaces For VR/AR/MR Environments

Lead Researcher: Marco Raoul Marini, Department of Computer Science, Sapienza University of Rome.

Aim. Design innovative user-interface (UI) concepts for virtual, augmented, and mixed reality (VR/AR/MR) that enable intuitive, accessible interaction without traditional input devices.

Process and products. The group first analyzed the requirements of UIs in immersive environments and identified possible "hands-free" interaction strategies—such as voice commands, eye movements, gestures, and walking. They then developed prototypes illustrating how these interactions might function within a cooking scenario, with potential extensions to surgical and industrial contexts. As an additional product, the group drafted a survey to assess citizens' familiarity with VR/AR/MR technologies and to explore the situations in which users would be interested in adopting such interfaces.

Research Line 3: Dentistry

Lead Researcher: Lorenzo Arcuri, Department of Life Sciences, Health, and Health Professions, Link Campus University of Rome; Ilaria Cammarota, Department of Chemical Science and Technologies, University of Rome Tor Vergata.

Aim. Increase public awareness of proper home oral hygiene and assess the prevalence of effective practices.

Process and products. In the introductory phase, participants witnessed a self-inspection protocol demonstration for the oral cavity held by the researcher, who gave particular attention to identifying lesions or unusual characteristics of the oral mucosa. After familiarizing themselves with the procedure, they then collaborated on the development of clear informational materials—combining images and text—to make the protocol accessible to a broad audience. The group then designed an initial survey aimed at investigating individuals' habits and lifestyles related to oral hygiene, to be administered alongside the self-inspection instructions. A second questionnaire was subsequently drafted to evaluate the ease of performing the procedure and to record observations made by participants. Over the course of the week, the group also began collecting preliminary responses to the first questionnaire from their personal networks.

Research Line 4: Digital And Physical Spaces In Prisons

Lead Researcher: Serena Cataldo and Luca Mazzali, Department of History, Humanities and Society, University of Rome Tor Vergata.

Aim. Deepen the understanding of prison conditions and spatial organization, examine the transformative impact of educational programmes on prisoners, and develop innovative proposals to improve these environments.

Process and products. At the beginning of the week, the group had the exceptional opportunity to meet a former prisoner who underwent a profound personal transformation by obtaining a university degree while in prison. This meeting laid the groundwork for subsequent discussions with researchers, who shared their work on the functions and meanings of space within carceral environments. Based on these insights, the group decided to focus on designing a study space within prisons that could be used by prisoners and staff. To support this work, two complementary surveys were planned: a quantitative questionnaire for prisoners, to gather data on their study experiences, needs, and aspirations; and a qualitative questionnaire for prison police staff, in order to understand how to improve educational spaces without compromising security and surveillance requirements. As an additional outcome, the group also planned a follow-up phase involving university students to compare their experiences with those of prisoners and jointly design improved educational spaces in prisons.

Research Line 5: Physics, Energy And Sustainability

Lead Researcher: Giovanni Mazzitelli and Ruggero Ricci, INFN Frascati National Laboratory.

Aim. Reflect on the concept of sustainability, understand the physical and technological constraints underlying it, and explore its real-life applications.

Process and products. After an initial brainstorming session aimed at establishing a shared definition of sustainability and analyzing its environmental, social, and economic dimensions, the group examined the physical meaning of sustainability and energy, progressively developing a more technical vocabulary. The group therefore decided to focus on the 2030 Agenda for Sustainable Development and specifically on lighting in private and public spaces. To raise public awareness and collect real data, participants designed a prototype "sustainability calculator", a tool that compares the costs (energy consumption, monetary expense, and CO_2 emissions) of using incandescent or compact fluorescent lamps versus LEDs and includes estimates of production and disposal costs. As a further development, the group proposed targeted applications of the calculator by key stakeholders, such as teachers, students, and industries, alongside a study to assess its impact on these different groups.

Discussion And Conclusion

At the end of the School, the organizers implemented a simplified evaluation procedure aimed at gathering feedback and reflections. This process involved (a) informal discussions with participating students and researchers, (b) two structured questionnaires, one administered to researchers and one to participating students, and (c) a debriefing meeting within the organizing team to review the results and identify areas for improvement. From this evaluation process, several noteworthy aspects emerged.

Firstly, the School successfully achieved its primary goal of engaging participants in citizen science through an innovative and participatory approach to authentic scientific research projects. All participants, despite their varying levels of expertise and different perspectives, actively contributed to the development of the research and had the opportunity to experience first-hand every stage of the scientific process. Participants developed a clearer understanding of both the importance and complexity of dividing the scientific problem into sub-problems, defining research objectives and questions, selecting appropriate methodologies, and sharing tools and preliminary results. They also recognized that scientific inquiry is far from the linear and orderly process often described in textbooks. Instead, it unfolds as a non-linear and sometimes intricate trajectory, characterized by failed attempts, dead ends, and unexpected changes in direction. Within this process, unconventional or interdisciplinary approaches can occasionally lead to effective solutions. Furthermore, regarding citizen science, participants had the opportunity to develop and practice related skills in a stimulating environment that encouraged discussion and critical exchange. This context allowed them to explore firsthand the potential of citizen science both as an educational tool, particularly for teachers, and as a research methodology for the experts involved. Finally, in full accordance with the principles of citizen science, the School has also generated tangible benefits for the research projects themselves. In addition to increasing their visibility, the activities carried out during the School have led to the development of future-oriented roadmaps, some of which can be implemented immediately and have the potential to produce rapid and significant results.

Despite these highly positive elements, we are fully aware that the implementation of the school has also revealed several weaknesses, particularly regarding the lack of more quantitative measures of its impact. A future edition should therefore include a systematic investigation of how the School experience influences students' and teachers' understanding of science practice, as well as the extent to which teachers and researchers intend to integrate the citizen science approach into their teaching practices or research activities. Furthermore, an interesting direction for future development would be to establish mechanisms that ensure the continuity of projects initiated during the School, for example creating a lasting community of students, teachers, and researchers that could collaborate and promote further growth of the research projects.

Nevertheless, we believe that the Citizen Science School Rome Technopole represented an innovative and successful model, with a considerable potential for replication in a variety of other contexts.

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What Does It Take to "Use" a Museum? A Closer Look at Museum Literacy

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In recent decades, museums have undergone a profound transformation from authoritative repositories of knowledge to participatory spaces of exchange, learning, and social engagement. Increasingly positioned as trusted institutions and as so-called "third places," museums now address complex societal challenges, contribute to democratic education, and foster dialogue across diverse communities. Despite these developments, museum audiences remain socially uneven, with educationally and economically disadvantaged groups still significantly underrepresented. This paper argues that improving accessibility and participation requires not only institutional change but also a clearer understanding of how museums can actively support and enable visitors to engage meaningfully with their offerings. To address this gap, the article revisits and expands the concept of museum literacy, originally introduced by Carol Stapp, and develops a differentiated, holistic framework. Drawing on established literacy models from fields such as digital, media, and scientific literacy, museum literacy is sketched as a three-level construct: (1) awareness and basic knowledge of museums and their affordances, (2) the practical application of skills within museums, including socio-cultural and emotional dimensions, and (3) the transfer of museum content to personal and societal contexts beyond the visit itself. Based on a small mixed-method study involving museum professionals, eight key dimensions of museum literacy are identified, ranging from curiosity and motivation to information processing, emotional competence, and appreciation of exhibits. The findings highlight which dimensions are considered particularly relevant and which are perceived as influenceable by museums. The paper concludes that fostering museum literacy is central to strengthening museums' social role, enhancing visitor engagement, and supporting inclusive, reflective, and democratic cultural participation.

Keywords: Lifelong learning, Out-of-school learning, Science Museums

Introduction

The social role of museums has changed significantly in recent decades. Moving away from the traditional image of the museum as a temple of information and knowledge, many museums are reorienting themselves towards becoming places of exchange and participation for all people in our society, increasingly developing into so-called "third places". This role extends far beyond the simple provision of information. Museums are now actively addressing major societal challenges. For instance, natural history and science museums engage with issues such as climate change, biodiversity and energy supply, while museums of cultural history, archaeology o art explore topics including cultural diversity and cultural influences on society, social developments and transformation processes. Ate the same time, they critically examine issues such as looted art, colonialism and the repatriation of objects. In this expanded role, museums function as mediators between different parts of society: they connect history with politics, the economy, and contemporary social issues. They promote exchange between different cultures and groups, as well as dialogue between art, culture and society at large. Particularly significant is the increasing attribution of a role in democratic education. By providing spaces for critical reflection, dialog, and participation, museums contribute to the strengthening of democratic social structures. As a result, their range of functions is expanding considerably beyond their traditional tasks.

As informal learning environments, museums address people of all ages. They act as an interface between leisure activities and education, providing low-threshold, flexible opportunities for learning and fostering dialogue on social issues. Another important aspect is the high level of trust museums enjoy among the public – not only in Germany, but internationally (Wilkening, 2021; Grotz & Rahemipour, 2024). Alongside changes in museums' self-conception, reflected in the revised ICOM definition of a museum (ICOM, 2022), museums are increasingly gaining importance for local communities as so-called third places (Dauschek, 2022). Nevertheless, despite these developments, many museums continue to primarily attract academically educated audiences, while educationally and economically disadvantaged groups remain significantly underrepresented (Hooper-Greenhill, 2006; Thoma et al., 2022; Wegener, 2016).

In order to enhance the accessibility of museums and facilitate more effective use, access, and understanding of their offerings, a multifaceted approach is necessary considering both institutional conditions and visitor-related factors. On the institutional side, museums must create environment that are welcoming and accessible to all segments of society. This includes measures such as reducing entrance fees, fostering inclusive and organizational cultures, implementing broad and effective communication strategies, and diversifying content by incorporating a wider range of knowledge, achievements, and perspectives that reflect societal diversity. Equally important is ensuring that museum staff more closely mirrors the diversity of society itself, thereby promoting representation within the institution. From the visitor's perspective, it is essential that individuals feel confident and prepared to engage with museums. This includes being aware of available content, activities, and learning opportunities, as well as possessing strategies to navigate and meaningfully use of what museums offer. Such preparedness enhances both the relevance and the depth of the museum experience.

There is little doubt that museums are intended to function as inclusive spaces for public engagement and, by definition, should be accessible to all individuals regardless of background or prior knowledge (BVMP, 2024). However, the concept of "accessibility without prerequisites" warrants critical examination. For example, extensive explanatory texts are of limited value to individuals who cannot read, even when written in simplified language. Conversely, oversimplifying information to accommodate broader audiences inherently diminishes the richness of content provided to visitors who possess foundational knowledge, owing to spatial and attentional constraints. The central challenge for museums therefore lies in developing differentiated offerings that address the needs of diverse audiences while enabling meaningful engagement across demographic groups. Layered communication strategies offer one possible approach to reaching the broadest possible audience.

In this context, a conceptual framework that highlights relevant dimensions of engagement may be helpful – both to support a greater inclusivity by minimizing unnecessary prerequisites while enhancing offerings, and to strengthen visitor competencies and foundational skills that enable deeper and more comprehensive use of museum resources.

The term museum literacy was first introduced in 1984 by Carol Stapp, who defined it by analogy to the more established concepts of "computer literacy" and "library literacy":

> By analogy, basic museum literacy means competence in reading objects (visual literacy), but bill museum literacy signifies competence in drawing upon the museum's holdings and services purposefully and independently. Museum literacy therefore implies genuine and full visitor access to the museum by virtue of mastery of the language of museum objects and familiarity with the museum as an institution. In a word, the museum literate visitor is empowered. (Stapp, 1984)

Stapp also pointed out that, while the use of libraries and computers is commonly taught within school curricula, the use of museums generally is not. However, her work does not provide a detailed description or operationalization of museum literacy. Although later initiatives – such as the EU project "museum literacy" (Gazzeri & Brown, 2010) - offer illustrative examples, a comprehensive and clearly defined conceptual framework remains lacking.

Adopting a holistic perspective, this article seeks to capture the various facets of the construct of "museum literacy". Specifically, it asks: What are its core components, and can these components be differentiated in ways that allow them to be systematically addressed, fostered, and measured?

Approach And Definition Of Museum Literacy

Current research demonstrates that literacy is fundamentally shaped by the cultural, political, and historical contexts of the communities in which it develops. Literacy is not only embedded in language and society, it also exists along a continuum across multiple levels that ultimately reflect an individual's cultural identity. Bélisle (2006) distinguishes three complementary approaches to literacy: an autonomous model, which conceptualizes reading and writing as technical skills; a sociocultural model, which emphasizes that literacy is always socially and ideologically embedded; and a "strong claim model", which represents the most far-reaching perspective and is based on the innovative potential of structured thought processes, thereby enabling the creation of something fundamentally new.

In a recent article (Kampschulte et al, 2025), we analyzed literacy models across various domains, including digital literacy (Martin & Gruziecki, 2006; Iordache, Mariën & Baelden, 2017), media literacy (Trültzsch-Wijnen, 2020; De Smedt et al., 2009), AI literacy (Long & Magerko, 2020) or scientific literacy (Gräber et al., 2013; Fischler, Gebhard & Rehm, 2018; Henriksen & Frøyland, 2000). Across all of these models, an elemental composition of literacy is always apparent, literacy consistently comprises a) a body of (subject-specific) basic knowledge, b) the abilities and skills required to use and apply this knowledge – typically in conjunction with tools – , and c) the application of this knowledge in private and/or social life contexts. Building on these discussions and with a view to the interpretation commonly used in English-speaking countries, this project adopts a concept of literacy that draws particularly on the digital literacy definitions proposed by Martin and Gruziecki (2006) as well as Iordache, Mariën, and Baelden (2017):

> Museum literacy consists of three components that build on each other: the basis is the organizational and content level, an awareness of the existence of museums, and basic knowledge about the affordances of museums and how they can be utilized. The second level is characterized by the ability to practically apply specific knowledge and skills in museums, including socio-cultural and emotional dimensions (e.g., being able to experience suitable emotions). The third level is the ability to apply the museum content in different life contexts – inside and outside the museum. This includes personal added value and, for example, the ability to engage in current discourses and thus participate in society.

Together, these three components increase the likelihood that individuals will use museums and benefit from them as spaces for personal development, social interaction, and participation.

The explicit inclusion of socio-cultural and emotional dimensions represents a specific feature of museum literacy. These aspects are far more central to museums than to other literacy concepts such as digital, or scientific, or computer literacy being used by Carol Stapp in the original definition. At this level, museums open up completely different channels of communication that run parallel to learning processes. In principle, these channels can support learning, they are also

crucial for achieving other visit objectives, such as social interaction during group visits or intense emotional experiences, for example when visiting memorial sites.

Study On Museum Literacy From A Museum Perspective

Table 1. Eight dimensions of museum literacy as found in the study.

	Dimension	Description
1	Curiosity, motivation, volition	Curiosity, motivation and the will to do something in the museum at all are the central basis for using a museum. Curiosity, especially intrinsic curiosity, is the desire to learn new things and discover hidden things. Motivation summarizes all motives that lead to a willingness to act. The deliberate, purposeful transformation of goals and motives into actions - and therefore results - is known as Volition. All three facets are closely linked to emotions and control the behavior in a museum.
2	Location and behavioral competence	This dimension encompasses the knowledge and skills needed to orient oneself in a museum in terms of time and space, to structure the visit and to behave appropriately in the location.
3	Information (processing) competence	The ability to use the information provided in a self-determined, confident and targeted manner.
4	Visual competence	The ability to interpret, evaluate and use information in the form of an image, sign or visual medium. Visual literacy is based on the idea that images can be "read" and that meaning can be discovered through this process of reading.
5	Prior knowledge and experience	This dimension includes both subject-specific knowledge and general prior knowledge that is relevant to the classification and understanding of the content offered, or experience that facilitates understanding.
6	Social competence	The ability and willingness to communicate and interact with other visitors or museum staff as appropriate to the situation.
7	Emotional competence	The ability to (correctly) perceive, understand and influence one's own and others' feelings. This includes emotional self-regulation in particular, but also the ability to allow emotions in the museum.
8	Appreciation of exhibits	Objects of cultural heritage are the basis of museums. Appreciation for these exhibits can arise in different ways (an object was selected for the museum vs. I know about the historical significance of the object) and increases the relevance for users.

To gain a deeper understanding of the skills and prerequisites required of museum visitors for museum literacy, we conducted a study aimed to identifying the knowledge implicitly or

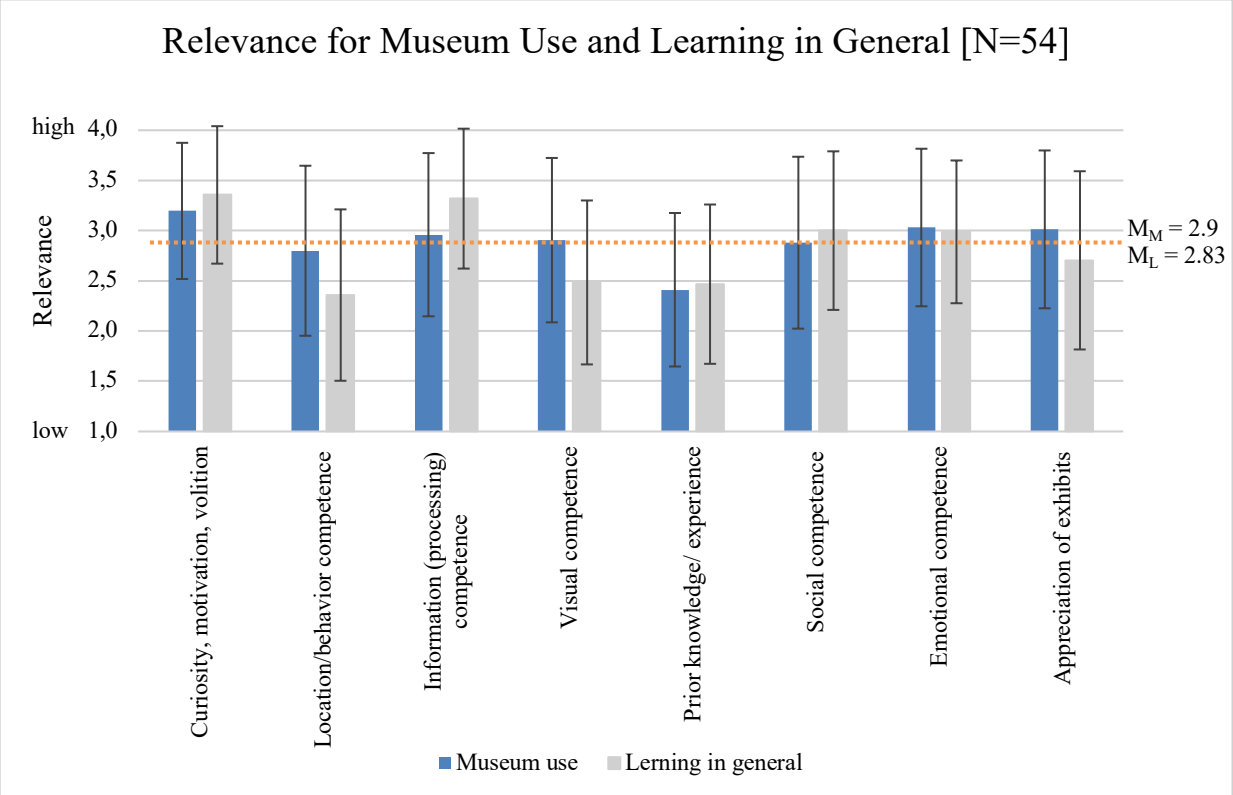
explicitly embedded in museums: In a first step, approximately 25 museum professionals and educational researchers participated in a round table discussion to identify what they considered to be the most important skills and prerequisites. These were grouped into seven overarching topics and further refined through an iterative, anonymized online survey process. In a second step, the experiences and perspectives of 15 purposively selected museum experts were collected for each of the seven topics, summarized, and analyzed using a qualitative online format.

Dimensions Of Museum Literacy

The results of the quantitative survey of museum experts revealed in the end eight dimensions that are relevant to the use of museums:

In the third phase of the study, these eight dimensions were evaluated by a larger group of museum professionals. A total of 54 participants were presented with the eight dimensions identified in the first phase and asked to assess their relevance. The aim was to distinguish whether the dimensions were perceived as more museum-specific or more general. The aim was to find out which factors could be particularly influenced by museums, either by improving e.g. their offers or communication, or with the aim to develop targeted opportunities to develop e.g. knowledge or skills.

Figure 1. Evaluation of the eight dimensions of museum literacy by museum experts in terms of their relevance to museums specifically or their relevance to learning in general.



Overall, the average relevance ratings for museums and for learning in general are very similar (MM = 2.9 for museums; ML = 2.83 on a 1–5 Likert scale). Museum professionals rated prior knowledge and experience as the least relevant dimension for both contexts. For a meaningful "use" of museums, curiosity, motivation, and volition were considered most important, followed by emotional competence and appreciation of exhibits. The largest differences between museums and learning in general – apart from location and behavioral competence – were found in the dimension of visual literacy. Visual literacy was rated as moderately important for museum use but considerably less important for learning in general. Information (processing) competence showed the opposite pattern: it was rated as slightly above average in importance for museums,

but as highly important for learning in general. These differences provide initial indications of which dimensions may be particularly promising starting points for further development on the museum side.

Discussion

Ultimately, all of these dimensions contribute to museum literacy and thus to a stimulating visitor experience. Of course, not all dimensions need to be fully developed in order to experience a good museum visit. Rather, they define a space of possibilities in which visitors can be situated. Which dimensions are activated, and to what extent, varies across museums, individuals, and visits. A six-year-old child, for example, will engage with different dimensions and with a different intensity than an adult who visits museums several times a month. Differences can also be observed within target groups: some visitors approach museums in a structured, knowledge-oriented manner, while others place greater emphasis on social or emotional dimensions.

Some of the dimensions outlined above are highly general in nature. Curiosity, motivation, and volition, for instance, play a role in most learning processes in everyday life. Other dimensions, by contrast, are highly museum-specific, such as location and behavioral skills. Given that the dimensions presented here were derived from a sample of museum professionals, they are strongly shaped by an institutional perspective. The next logical step is therefore to examine these dimensions from the visitors' perspective and to compare internal external viewpoints. Established evaluation models from other literacy domains can serve as a basis for this process and be adapted to the museum context.

In a changing social landscape, museums are widely regarded as trusted institutions, placings them in a strong position to act as independent and reliable sources of information. At the same time, this trust cannot be taken for granted, particularly as political influence on cultural institutions becomes increasingly visible. Museums therefore need to actively maintain and strengthen their credibility – by remaining spaces of enjoyment and inspiration, while also functioning as dependable sources of knowledge and as platforms for open dialogue and critical reflection.

The promotion of museum literacy plays a pivotal role in achieving these objectives. From an institutional perspective, it supports the development of more inclusive programs tailored to the needs of diverse audiences. From the visitors' perspective, individuals are supported in effectively accessing, understanding, and making use of the resources and experiences offered by museums. By bridging gaps in understanding and accessibility, museum literacy contributes to a more informed and interconnected society.

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A Scoping Review On Using Virtual Reality To Visit Informal Environments In Primary Science Education

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Virtual reality (VR) is progressively being explored as a means of facilitating access to informal learning environments in primary science education. These environments, such as museums, science centres, and natural settings, are widely recognised for supporting engagement, inquiry, and meaningful science learning, yet remain inaccessible to many schools due to logistical and financial constraints. This study presents a scoping review of literature published between 2014 and 2024 to map patterns and developments in the use of VR for visiting informal learning environments in primary science education, as well as to identify emerging challenges and opportunities. Guided by the Informal Science Learning framework, 25 empirical studies were systematically analysed. The preliminary findings indicate a growing emphasis on immersive virtual field trips using technologies such as 360-degree video and head-mounted displays to enhance learner engagement and inquiry-based learning. The review also highlights persistent challenges related to cost, technical infrastructure, health concerns, and teacher preparedness, alongside opportunities for improving accessibility and inclusivity in science learning. By synthesising current research, this scoping review provides an overview of how VR is being used to extend informal science learning opportunities for primary learners and identifies key considerations for educators, researchers, and technology developers.

Keywords: Out-of-School Learning, Primary Science Instruction, Virtual Reality

Introduction and Conceptual Framework

Virtual reality (VR) is increasingly being integrated into educational contexts, offering immersive and interactive learning experiences that extend beyond the constraints of traditional classroom-based instruction (Lopes et al., 2024). In primary science education, VR has attracted growing scholarly attention for its potential to simulate access to informal learning environments such as virtual museums, science parks, zoos, and natural ecosystems (Han, 2021). Through these virtual experiences, learners can explore scientific phenomena and contexts that may be geographically distant, logistically inaccessible, or financially prohibitive, thereby addressing persistent barriers related to cost, safety, and time constraints in school-based science learning (Han, 2021; Lopes et al., 2024).

Research suggests that VR-supported learning can enhance learner engagement, conceptual understanding, and motivation by enabling experiential and inquiry-oriented approaches to science education (Won et al., 2023; Xie & Zhang, 2024). The affordances of VR allow learners to observe dynamic processes, manipulate variables, and interact with representations of complex scientific concepts that are difficult to visualise through textbooks or static media alone (Han, 2021). These features are particularly valuable when VR is used to replicate informal learning environments, where exploration, curiosity, and learner-driven inquiry are central to knowledge construction and the development of critical thinking skills (Won et al., 2023).

Considering its pedagogical potential, the integration of VR into primary science education is accompanied by notable challenges. Studies have reported barriers related to hardware costs, technical infrastructure, limited teacher training, and concerns about learner well-being, including cognitive overload and motion sickness (Barrett et al., 2023; Han, 2021; Mohale, 2024). At the same time, VR presents important opportunities to support inclusive and equitable learning by accommodating diverse learning needs, providing multimodal representations, and broadening

access to high-quality informal science experiences that may otherwise remain unavailable to many learners (Lampropoulos & Kinshuk, 2024; Lopes et al., 2024).

To synthesise and make sense of this growing body of literature, this scoping review is guided by the Informal Science Learning (ISL) framework as articulated by the National Research Council (2009). The ISL framework conceptualises learning as a socially mediated, interest-driven process that occurs across diverse contexts beyond formal classrooms, including museums, science centres, outdoor spaces, and digitally mediated environments (National Research Council, 2009). It emphasises key dimensions such as learner engagement, meaning-making, participation in scientific practices, and the role of learning environments and tools (Photo & Shabalala, 2025). Framing this review through the ISL lens enables a systematic mapping of how VR has been used to facilitate access to informal science learning environments in primary education, while also illuminating the patterns, developments, challenges, and opportunities that have emerged in this field between 2014 and 2024. Guided by the Informal Science Learning framework, this scoping review addresses the following research questions:

1. What patterns and developments are evident in the use of virtual reality to facilitate access to informal learning environments in primary science education between 2014 and 2024?
2. What challenges and opportunities have emerged in using virtual reality for informal learning environments in primary science education during this period?

Methods

This scoping review employed a systematic methodology to gain an in-depth understanding of previous research on the use of VR to facilitate access to informal learning environments in primary science education and to identify gaps for further exploration. Following the framework proposed by Gough (2017), the review was guided by clear research questions. It included systematic activities such as the identification of relevant research, study selection, screening, synthesis, and the formulation of evidence-based claims. The focus was on publications released between 1 January 2014 and 31 December 2024, providing perceptions on how the field has evolved over this period.

Study Selection And Screening

Study Identification

This scoping review followed PRISMA principles (Liberati et al., 2009). The initial search was conducted using EBSCOhost and included databases such as Academic Search Premier, Education Source, and Applied Science & Technology Source. The search terms incorporated variations of “virtual reality,” “informal environments,” “primary science education,” and related keywords such as “outdoor learning,” “field trip,” “nature reserve,” “science park,” and “natural environment” to capture the range of contexts in which virtual reality is implemented. The review focused on studies published between 2014 and 2024, reflecting recent advancements in VR technology and its applications in education. The initial search yielded 389 articles, and after the removal of 154 duplicates, 235 studies entered the screening phase for further evaluation (see Figure 1).

Manual Screening

Following the initial identification of 235 articles, a manual screening process was conducted. Articles were included if they (1) focused on virtual reality technologies in informal learning environments, (2) pertained to primary science education, and (3) were peer-reviewed empirical studies. Non-peer-reviewed articles, unrelated fields, and incomplete records were excluded.

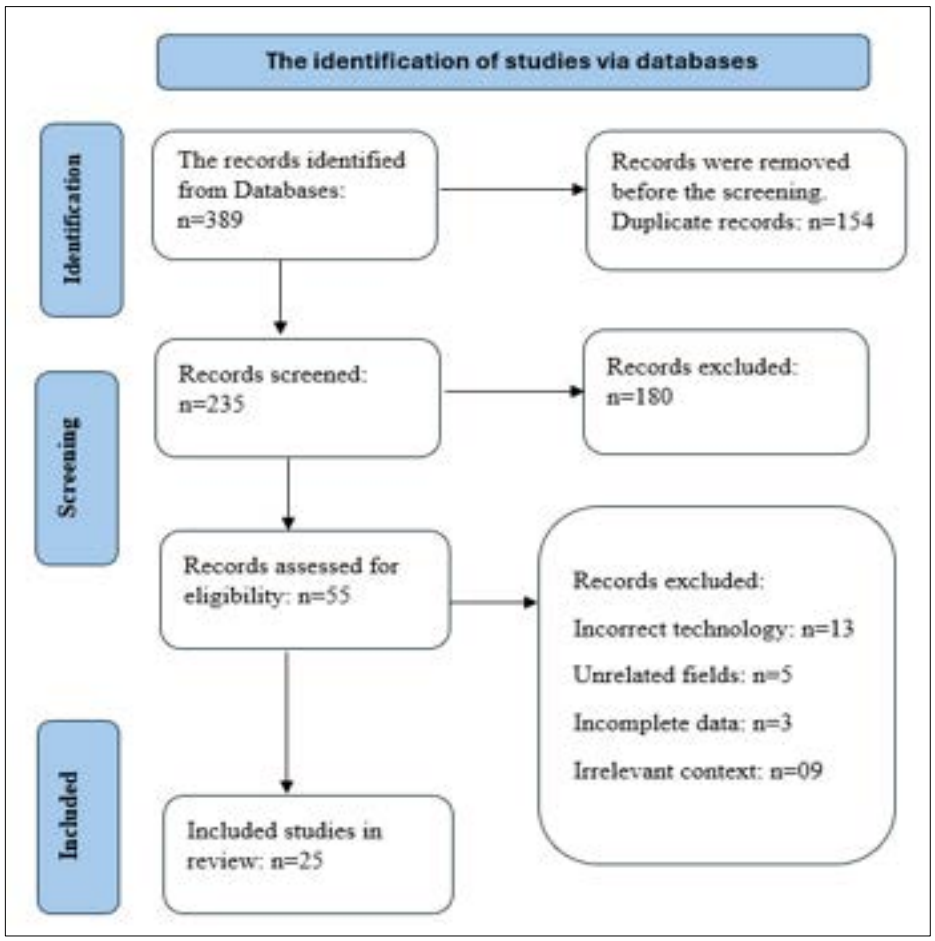
Eligibility

The first author conducted the full-text screening of the remaining 55 studies. Only studies written in English, peer-reviewed, and published between 2014 and 2024 were included. Based on the eligibility criteria, 30 studies were excluded: 13 for incorrect technology (Calvert & Abadia, 2020), 5 for unrelated fields (Goff et al., 2018), 3 for incomplete data, and 9 for irrelevant context (Huang et al., 2019). After the full-text review, 25 studies were included in the final analysis.

Data Extraction

Study characteristics were extracted and coded to address the research questions. The coding process was conducted inductively by the first author and verified for consistency. Each study was analysed for its purpose, framework, participant population, type of VR used, informal learning environment context, methodology, setting, and reported challenges and opportunities.

Figure 1: PRISMA Flow Chart (Liberati et al., 2009)



Preliminary Results And Discussion

Following a systematic scoping review process, 25 studies examining the use of virtual reality (VR) to facilitate access to informal learning environments in primary science education were identified and analysed. These studies, published between 2014 and 2024, reflect a steady growth in scholarly interest in VR as a means of extending science learning beyond the formal classroom into digitally mediated informal contexts. Consistent with the aims of a scoping review, the findings focus on mapping key patterns, developments, challenges, and opportunities rather than evaluating the effectiveness of interventions.

RQ1: What Patterns And Developments Are Evident In The Use Of Virtual Reality To Facilitate Access To Informal Learning Environments In Primary Science Education Between 2014 And 2024?

Emergence Of Immersive Virtual Field Trips (Vfts)

A prominent development across the reviewed literature is the widespread adoption of immersive virtual field trips (VFTs) as a primary application of VR in informal science learning. Many studies reported the use of VR to simulate visits to museums, science centres, natural habitats, and geographically remote environments. Han (2020) demonstrated that VR-supported VFTs effectively addressed logistical and financial barriers associated with traditional field trips, while still providing learners with meaningful experiential learning opportunities. Technologies such as 360-degree videos and head-mounted displays (HMDs) were commonly employed to enhance learners' sense of presence and immersion, which studies associated with increased engagement and curiosity (Cheng, 2022; Garcia et al., 2023).

Beyond access, several studies indicated a shift towards designing VFTs that support exploration and inquiry, allowing learners to navigate environments, observe scientific phenomena, and interact with contextualised content. This trend reflects a broader movement toward experiential and learner-centred approaches in primary science education, aligning closely with the principles of informal science learning.

Addressing Accessibility And Inclusivity

Another notable pattern concerns the use of VR to promote accessibility and inclusivity in primary science education. Multiple studies highlighted VR as a practical alternative for schools facing financial, geographical, or safety-related constraints that limit participation in physical field trips. Garcia et al. (2023) reported that VFTs offered scalable solutions for under-resourced schools, while Cheng (2022) emphasised the value of localised and culturally relevant VR content in making science learning more meaningful for diverse learner populations. Collectively, these findings suggest that VR-mediated informal learning environments can contribute to more equitable access to high-quality science experiences.

RQ2: What Challenges And Opportunities Have Emerged In Using Virtual Reality For Informal Learning Environments In Primary Science Education During This Period?

Technical And Pedagogical Barriers

Regardless of the documented benefits, the reviewed studies consistently identified technical and pedagogical barriers to the effective use of VR. Health-related concerns, including motion sickness, eye strain, and physical discomfort, were frequently reported as limitations affecting sustained learner engagement (Han, 2020). In addition, the cost of VR hardware and supporting infrastructure remains a significant obstacle, particularly for schools with limited budgets (Liu et al., 2020). From a pedagogical perspective, several studies pointed to challenges related to curriculum alignment and insufficient teacher preparation. Ramsurrun et al. (2024) noted that teachers often lacked the confidence and professional support required to integrate VR meaningfully into science learning activities, highlighting the need for targeted professional development.

Fostering Engagement And Inquiry-Based Learning

At the same time, the literature reveals substantial opportunities for VR to enhance informal science learning through engagement and inquiry-based approaches. Klippel et al. (2020) demonstrated that relatively low-cost VR solutions, such as 360-degree environments, can still provide immersive and interactive experiences that support exploration and critical thinking.

Several studies emphasised that VR environments encourage learner curiosity, sustained attention, and active participation, particularly when aligned with inquiry-oriented tasks. These opportunities position VR as a promising tool for enriching informal science learning experiences in primary education when implementation challenges are adequately addressed. Table 1 provides a consolidated overview of the key patterns, challenges, and opportunities identified across the 25 studies included in this scoping review.

Table 1: Summary of Key Patterns, Challenges, and Opportunities Identified

Focus Area	Key Findings from Reviewed Studies
Dominant VR Application	Immersive virtual field trips simulating museums, natural environments, and science centres
Technologies Used	360-degree videos, head-mounted displays, and interactive VR environments
Educational Purpose	Enhancing access, engagement, exploration, and inquiry-based learning
Accessibility & Equity	Reduced logistical and financial barriers; scalable alternatives to physical field trips
Technical Challenges	Hardware costs, motion sickness, and infrastructure limitations
Pedagogical Challenges	Curriculum integration difficulties, limited teacher preparedness
Key Opportunities	Increased learner engagement, inquiry-based learning, and exposure to otherwise inaccessible environments

Practical Implications

The preliminary findings of this scoping review suggest that virtual reality has considerable potential to enhance learner engagement and support inquiry-based learning in primary science education by facilitating access to informal learning environments. For teachers, these initial insights indicate the value of incorporating VR-supported virtual field trips and exploratory activities into lesson design to stimulate curiosity, observation, and conceptual understanding, particularly in contexts where physical access to informal science settings is constrained. For researchers, the findings highlight the need for further empirical work that examines scalable and sustainable implementation models, with particular attention to challenges related to cost, infrastructure, and learner well-being. From a development and policy perspective, the preliminary evidence points to the importance of designing affordable, portable, and curriculum-aligned VR tools that are responsive to the realities of resource-limited school contexts, thereby supporting more equitable access to informal science learning opportunities.

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Gaining Insight Into Rural, Underserved Students' Experiences Of At-Home, Justice-Centered STEM Kits And Books

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Out-of-school activities have the potential to broaden participation in STEM, especially for groups with less access to school-based opportunities. In this exploratory, mixed-methods study, at-home STEM kits were mailed to rural middle school students to address inequities in STEM access. The kits included nonfiction trade books featuring the stories of underrepresented minority STEM professionals and content-aligned STEM kits. The quasi-experimental design used repeated measures over four sets of mailed-home STEM kits to gauge students' responses to generic prompts (control) compared to those that addressed social justice constructs (intervention). Morales-Doyle's justice-centered science pedagogy framework was adapted as Justice-centered STEM Framework (JCSF) and guided the data analyses. The research question was: How did students respond to the at-home intervention, and were there differences between the intervention group and the control group? Findings indicate that the at-home STEM kits led to similar responses between both student groups. Overall, the analyses revealed how these students operationalized salient aspects of the JCSF around critical consciousness, academic success, and cultural competence. Within these three elements, themes were coded that highlighted students' perceived reactions: STEM identity, self-efficacy, authentic STEM, enjoyable/engaging, learning, familial sharing, quality materials, learning, awareness, and inspiring. Implications and lessons learned are discussed.

Keywords: social justice, STEM kits, trade books

Introduction

In the Spring of 2020, many teachers had to switch from in-person, synchronous teaching to remote, asynchronous classrooms overnight (Sun et al., 2020) as a result of the global pandemic. Many schools in the United States (U.S.) did not return to in-person instruction in the 2021-2022 school year following the initial impact of COVID. In addition to in-school impacts, the pandemic impacted after-school activities, which were suspended almost immediately (Moody, 2020) and were slow to return in many parts of the U.S.

One promising way to address this programming shortfall was through at-home interventions. In prior research, students and their family members had received high-quality STEM materials at home, which they completed with family members they found highly engaging (Gutierrez et al., 2025). However, sending home materials necessarily involves family members, who may be unclear about their role (Garcia-Reid, 2007; Hill & Torres, 2010; LaRocque et al., 2011). In addition, parents of children in educational systems that have underserved students, from lower socioeconomic (SES) homes, and who are racial/ethnic minorities are often distrustful of school systems (Hill, 2011). Multicultural literature can assist these students in their identity formation (Hseu & Hetzel, 2000), giving them a sense of belonging and acceptance in society. This study aimed to engage rural middle school students in the southeastern U.S. with an at-home intervention that included a hands-on STEM kit and a related trade book featuring multicultural characters, and to investigate whether social justice-oriented prompts affected their perceptions of these STEM materials.

Literature Review

Science Trade Books

Science trade books are important curriculum materials that can be used in K-12 science classrooms to strengthen students' literacy skills, assist students in learning science content, and ultimately increase participation in the STEM workforce (NSF, n.d.). In 1973, the National Science Teaching Association (NSTA), in cooperation with the Children's Book Council (CBC), created the Outstanding Science Trade Books for Children, a list of recommended trade books (NSTA, n.d.). Some criteria for selection include books that contain clear, up-to-date science content that is not oversimplified. Also, the books are free of gender, ethnic, and socio-economic biases; they are at the appropriate level for the audience and contain illustrations that are accurate in size, scale, and color (Texley, 2008). The science trade books provide opportunities for students to learn science practices (Texley & Ruud, 2017).

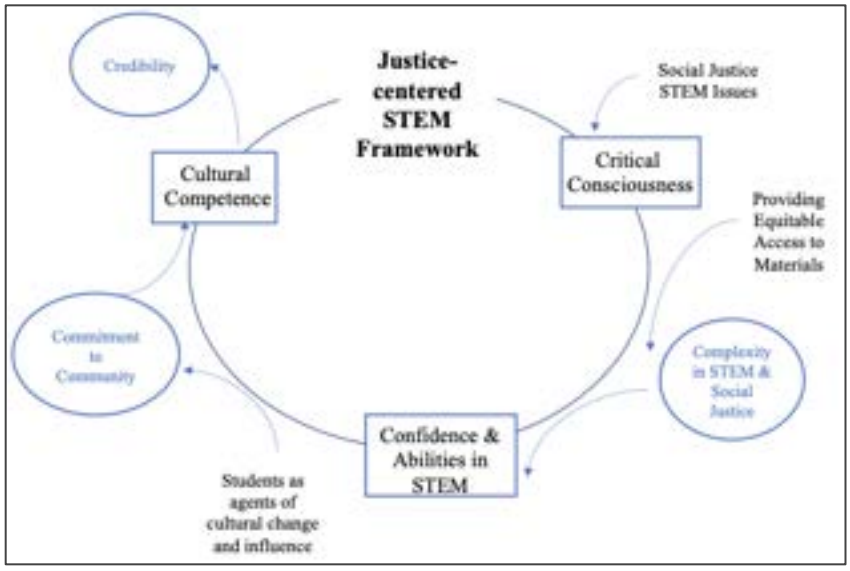
STEM Kits

Prior research has shown that students prefer learning science through activities with kits rather than just using textbooks (Houston et al., 2008). Analyzing qualitative and quantitative data from 588 elementary students (grades 3-5), Houston and colleagues discovered that using science kits was associated with more effective science instruction in terms of greater student satisfaction. In informal STEM settings, such as after-school programs and STEM camps, the use of STEM kits can broaden the participation in STEM of underrepresented groups (Newton et al., 2020).

Theoretical Framework

Justice-centered science pedagogy (Morales-Doyle, 2017; Figure 1) is a framework built on culturally relevant and critical pedagogy to address inequities in science education and potentially lead to social transformation. Drawing upon prior work (Ladson-Billings, 1995), culturally relevant pedagogy requires students to 1) experience academic success, 2) develop cultural competence, and 3) develop critical consciousness, challenging the current social order. The third criterion relates to Freire's work with critical pedagogy, emphasizing *conscientizacao*, a process by which people begin to view themselves as capable of eliminating oppression by transforming reality (Freire, 2020, 2021a, 2021b; Freire & Macedo, 2005). People develop a critical consciousness from education that elucidates the historical and political conditions that created inequitable social circumstances.

Figure 1. Justice-centered STEM Framework (modified from Morales-Doyle, 2017).



Research Design

This study used a convergent mixed methods design (Creswell & Plano Clark, 2018). The study collected repeated measures from students from five middle schools over six months to assess whether there would be differences in perceptions of justice-oriented constructs (e.g., critical consciousness, commitment to community) depending on whether they were responding to a neutral (control) or a justice-oriented prompt (intervention). Students received up to four STEM kits and justice-oriented trade books. Two of the five schools were randomly assigned to receive justice-oriented question prompts, while the remaining three schools received neutral question prompts for the STEM kits and trade books. Surveys included quantitative data from 6-point Likert-scale items and a qualitative open-ended question. The quantitative and qualitative data were collected simultaneously but analyzed separately, and the results were merged to address the third research question (Creswell & Plano Clark, 2018).

Research Questions

This study sought to understand how students participated in and responded to social justice-oriented trade books and STEM kits mailed to their homes during COVID-19.

1. How did the participation compare between students who received neutral (control) prompts and those who received social justice-oriented prompts (intervention)?

2. How did survey responses compare between students in the control and the intervention groups?

3. How did students describe what they gained from their experiences, and did they differ by group?

4. How do the qualitative themes map onto the justice-centered STEM framework?

Methods

Project Design

This project aimed to promote meaningful student and parent discussions around diversity, equity, and inclusion in STEM by increasing their awareness of, interest in, and positive perceptions of STEM professionals, fields, and careers. Built on pilot work conducted with rural middle school students (Blanchard et al., 2023; Gutierrez et al., 2025), this innovative project extended academic activities into the home by mailing home an interesting and challenging multicultural, nonfiction trade book with a STEM kit for at-home STEM-related investigations and reading.

Rationale For Materials Selected

The books were selected to highlight individuals who are traditionally underrepresented in STEM fields, to serve as role models (Table 1). The featured individuals revealed aspects of their lives, their character, and their choices, and highlighted adversities they may have faced. Two African American Females and Two Males (one African American and one Hispanic) were the subjects of the selected non-fiction historical trade books. For this study, all four books had these six common characteristics: 1) contained a simplified version of a story, 2) demonstrated a non-stereotypical appearance of a scientist, mathematician, or engineer, 3) were age-appropriate, 4) focused on the process of science, math, or engineering (struggles and perseverance) in contrast to science, math, or engineering as a miraculous event, 5) contained accurate information, and 6) had colorful illustrations (Delgado, 2021; Kibler & Chapman, 2019). Kiwi Crate Kits (Kiwico, 2022) were selected based on their quality, success, affordability, and ability to be mailed. As seen in Table 1, the book and STEM kits were paired on a related topic.

Table 1. Kit-book sets.

Kit	Book	STEM Kit
1	*Counting on Katherine* by Helaine Becker	Bottle Rocket
2	*The Boy Who Harnessed the Wind* by William Kamkwamb	Hand Crank Flashlight
3	*Seeds of Change* by Jen Cullerton Johnson	Drip Irrigation
4	*Esquivel! Space-Age Sound Artist* by Susan Wood	Light Up Speaker

Research Context

Five middle schools in the southeastern U.S. (partners in a STEM club project) agreed that kits could be mailed to their students' homes. All participating schools were classified as Title I, a U.S. federal education program that provides additional funding to schools with a majority of low-income students (Elementary and Secondary Education Act, 2015). The majority of the students (86% to 95%) identified as underrepresented minorities (URM), and 98% of the students at three of the participating schools qualified for free or reduced-price lunch (School Digger, 2022). Historically, end-of-grade test scores were significantly below those of their state (except for one school).

Participant Recruitment & Participation

The school's science teachers and academic coaches invited approximately 30 students from each of the five middle schools, grades 5th-8th, to participate in the project. Students received welcome letters with QR codes and a web link to a Qualtrics survey to sign up to participate in the project. Kits were mailed to the students' specified guardian, or (if requested) mailed to the student's school, to then be taken home by the student. A liaison teacher at each school encouraged students to participate.

Each kit and book had an associated survey that students could access through a web link or a QR code, to take after completing both the kit and the book. Once students completed both surveys, they were mailed the following kit and book. Students could receive up to four packages, each with a STEM kit and a related book. Due to lower-than-expected student enrollment, teachers at four schools received a classroom set of kits and books to share with their students approximately halfway through the Spring semester. One school incorporated the kits into its after-school STEM Club program and included a total of three kits in its club activities. A spike in survey responses on one date suggests that these kits and books were done during a club meeting, but otherwise, no data were collected that could verify the location of the reading and kit activities. Reminder postcards were mailed to students approximately two weeks after each kit/book mailing to encourage student participation.

Survey

The survey prompts were developed by the first and second authors, based on constructs of the modified Morales-Doyle framework (2017). Before distribution, the survey items were shared with other science educators (i.e., faculty, graduate students) and middle school students to provide face and content validity for the items (Sartori & Pasini, 2007). Through Qualtrics, survey questions utilized a 6-point Likert scale, with 1 represented *Completely disagree*, while 6 reflected *Completely agree*.

The students from two randomly selected schools received neutral survey prompts as a control group, reflecting activity completion and comprehension. As an intervention group, students from the other three schools received prompts informed by Morales-Doyle's justice-centered science pedagogy framework (2017; Table 2).

Table 2. Book and kit survey questions.

	Neutral Survey Items	Justice-Oriented Survey Items	Justice-Oriented Construct
Book 1	The main character faced opposition or challenges in the story.	Sometimes doing what is right, or ethical, is difficult.	Critical Consciousness
Book 2	The main character was very successful.	Others in the community were impacted by the abilities of the main character.	Commitment to Community
Book 3	The main character became well known.	The main character was committed to making their community a better place.	Commitment to Community
Book 4	This story made me think that the lead character was pretty special.	This story made me believe that if I wanted to, I could become a mathematician [varies by book].	Confidence & Ability in STEM
Book 5	People who impact the community are important.	This story made me believe I can impact my community in a positive way.	Commitment to Community
Book 6	I read all of the book.	I read all of the book.	Equitable Access to Materials
Book 7	I shared the book with a friend or a family member.	I shared the book with a friend or a family member.	Commitment to Community
Book 8	This was a biography, a story about someone's life.	This book is an example of how science [varies by book] can change the culture or habits of one's community.	Cultural Competence
Kit 1	I enjoyed working on the kit.	Working on the kit made me feel like I could overcome other challenges that I face.	Critical Consciousness
Kit 2	After doing this kit, I am looking forward to the next one.	After doing this kit, I gained confidence in my abilities in STEM.	Confidence & Abilities in STEM
Kit 3	This kit made me feel capable.	I think I could do some things in STEM that could improve my community.	Commitment to Community
Kit 4	I completed all of the kit.	I completed all of the kit.	Equitable Access to Materials

Open Response Coding

An inductive process was used to identify the themes from the open response items. Two coders read through all the comments and identified possible themes. Common themes that emerged from the statements about the kits included: STEM identity, self-efficacy, authentic STEM, enjoyable/engaging, learning, and familial sharing. Statements for the books repeated several previous themes, including enjoyment/engagement, learning, familial sharing, and self-efficacy. New themes also emerged, such as awareness, quality materials, and inspiring. After the codes were determined, one of the coders read through the statements and broke them into discrete units to delineate coding segments, a process referred to as unitization (Campbell et al., 2013). After the statements were segmented, the two coders independently assigned codes. After all items were coded, the codes were compared between the co-coders. A rate of 90% agreement was calculated for interrater reliability. Disagreements were then discussed until 100% agreement was reached for all statements (Patton, 2015).

Analyses and Findings

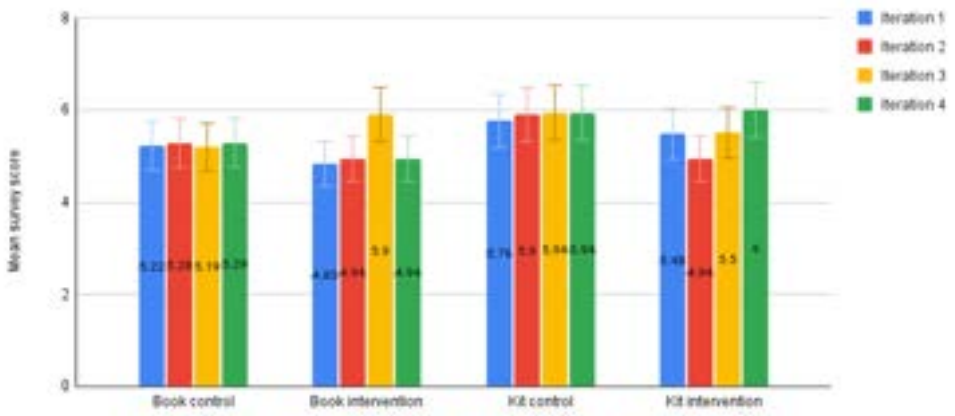
RQ1: Project Participation And Attrition

The project participants ($N = 110$) for both groups primarily self-identified as URM. The neutral group was more likely to be female (58%) and enrolled in 6th grade (44%). The justice-oriented group was more likely to be male (54%) and in 7th grade (71%). Comparing the survey completion rate of books to kits, students completed more kits across all interactions, except for the justice-oriented group in the fourth iteration, after the kits were mailed to teachers. The neutral group participated more throughout the project than the justice-oriented group, except for trade book 3 (*Seeds of Change*) and trade book 4 (*Esquivel! Space-Age Sound Artist*).

RQ2: Quantitative Analysis: Students' Responses To Justice-Oriented Survey Items

Kit scores were higher than trade book scores on the justice-centered survey constructs, except for Kit 2, Intervention. All scores were considered high as values represented *mostly agree (5)* or *completely agree (6).* Mean scores for the surveys increased across the iterations. Trade book means were lower than kit means. The justice-oriented means were lower than the neutral means for most data points, though the values differed only slightly in both conditions. The greatest difference between neutral (M =5.90) and justice-oriented ($M = 4.94$) survey means occurred with Kit 2, with a difference of 0.96 points. Statistical tests were conducted through t-tests, but no statistically significant relationships were found (Figure 2).

Figure 2. Book and Kit Survey Means.



RQ3: Qualitative Analysis: Themes From Open-Response Items

Both groups of students wrote positive comments toward the books and kits, and their responses aligned with the social justice concepts within the books, regardless of their group. The common themes that emerged from the statements included: STEM identity, self-efficacy, authentic STEM, enjoyable/engaging, learning, and familial sharing (Table 3). New themes that emerged with the book included awareness, quality materials, and inspiring.

Table 3. A Priori Codes in Open-response Analysis.

Code	Definition	Exemplar Statements
Learning	Learning new information or about STEM concepts.	***…****it tells about the environment and how we are hurting it.* (*Seeds of Change*, 8th grade, Hispanic Female)
Self-efficacy	Students expressed motivation to do something, take action, especially within their community.	*…the book was great…****to think how to make a change in the world.*** (*The Boy Who Harnessed the Wind*, 8th grade, Hispanic Female)
Enjoyable & Engaging	Fun or engaging experience in completing the activity/reading the book.	*Working on the STEM kit I thought it was very fun and creative.* (Bottle Rocket, 8th grade, Black Female)
Authentic STEM	When students spoke about experiencing STEM as it would occur in a lab, in contrast to a scripted experiment.	*My seeds grew a lot but when I took them out to the sun they died so I will plant more.* (Drip Irrigation, 6th grade, Hispanic Female)
STEM Identity	Positive beliefs toward their competence and performance in science, as well as believing others will recognize them as a scientist, engineer, or mathematician.	*It is bringing my dream of being able to build electronics true.* (Crank Flashlight, 6th grade Male, unknown race/ethnicity)
Familial Sharing	Students shared these experiences with their families.	*I also got to do it with my younger siblings, which was nice.* (Bottle Rocket Kit, 8th grade, Hispanic Female)
Quality Materials	Appreciation for the narrative and quality of materials.	*I think the book was really good* (*Esquivel Space Age Sound*, 6th grade, Hispanic Female)
Inspiring	Books gave rise to positive or creative feelings.	*I found this book inspiring because it showed that no matter what comes your way, you should never give up for what you believe in.* (*Counting on Katherine*, 8th grade, Black Female)
Awareness	Greater awareness toward critical issues with race, gender, and life situations.	*It helped [me] realize that everyone can do anything as long as you work hard.* (*The Boy Who Harnessed the Wind*, 6th Grade, Hispanic Female)

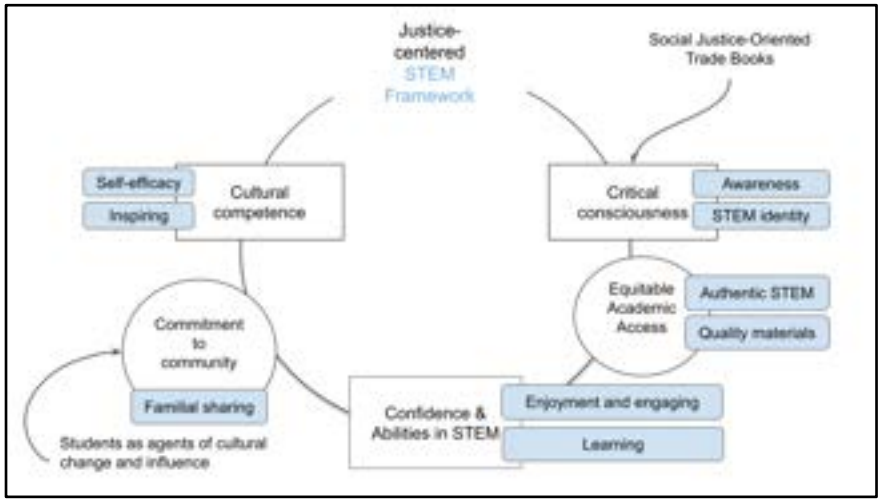
Themes Integration With A Justice-Centered STEM Framework

The fourth research question asked how the themes from the open-ended responses mapped onto the justice-centered STEM framework. The themes identified in the students' statements correlate

with the concepts of the JCSF (Figure 3). The themes of STEM identity and awareness are aspects of the component **critical consciousness**, as students could visualize themselves as real STEM professionals through the kits and relate to the social, racial/ethnic, and gender aspects of the characters in the stories. The themes of authentic STEM and quality materials reflected **equitable academic access** as students could complete real STEM experiences and learn about the challenges STEM professionals faced in the trade books. Prior research supports using quality STEM experiences in out-of-school activities as learning tools to reach underserved students (Blanchard et al., 2023).

The framework component **confidence and abilities in STEM** was reflected by two themes, learning and enjoyable/engaging. These components were critical in helping students persist in tasks and gain confidence in their abilities, as shown in prior research (Blanchard et al., 2023; Morales-Doyle, 2017). Familial sharing was the theme that related to **commitment to community**, as students wrote about sharing their experiences with their siblings and parents. In prior research, high school students reflected on this component when they presented their soil project at a family science night (Morales-Doyle, 2017). Lastly, **cultural competence** was reflected in students' sense of self-efficacy and inspiring themes as students wrote about how they could be agents of change and have critical roles in the future of STEM. This finding resonates with the effects of Laughter and Adams (2012) in their study of middle school teachers who used a short story, The Space Traders, to create classroom discussions about scientific bias and their larger societal contexts.

Figure 3. Components of the Justice-centered STEM Framework, with themes.



Note. The coded themes are included in rectangles shaded in blue. Blue font reflects changes from the original justice-centered science pedagogy model of Morales-Doyle (2017).

Limitations

A major limitation was the participation attrition, likely a result of an inability to communicate directly with parents or guardians, limited involvement of teachers, and the apathy that followed extended issues from COVID. Another limitation is the relatively small sample of students who participated in the study, all of whom were enrolled in rural middle schools in underserved communities.

Discussion

This at-home STEM intervention began as a response to COVID; none of the middle schools felt able to carry out STEM club activities when navigating the logistics of students returning to the classroom. Although it was anticipated that students would be excited about the kits and books and eagerly participate, student participation in the kits began slowly, and it took multiple

reminders via postcards mailed to homes to try to increase the level of participation. Of the students who began the project, a limited number continued past the second kit. These findings are similar to findings in another study, when students from an active STEM club carried home STEM kits (Gutierrez et al., 2025).

It was anticipated that the repeated measures of justice-oriented prompts might lead, over time, to increased student perception of their agency and involvement in their communities. However, findings revealed insignificant differences in participation, completion, and responses between the neutral and justice-oriented groups. The lack of difference in the findings between the two groups suggests that the project materials themselves - the STEM kits and the social justice-oriented trade books - were what led to students' perceptions, rather than the difference in the prompts (Blanchard et al., 2021; Smith, 1995; Steiner, 1998).

It also was anticipated that the students who received prompts that explicitly related to justice-oriented ideas would, over time, have responses that were more aligned with these constructs. The mean survey scores increased with iterations, potentially reflecting greater engagement and increased agreement with justice-oriented prompts as the project progressed. Yet, the analyses of the students did not reveal any statistically significant differences. It was hoped that students would share the trade book and/or kit with family members, yet they reported that they mostly did not. This was unlike the Gutierrez et al.'s (2025) study, in which students were explicitly asked to work with their family members and audio record the interactions.

Conclusions And Implications

The findings of this study lead to several conclusions and implications. First, students responded very positively to the at-home STEM kits and the social justice-oriented trade books. This suggests that the curriculum materials were of the right difficulty level and relevant or of sufficient interest for the students. Second, student participation fell off quickly. This was likely the result of a lack of strong ties to an active STEM Club or instructor support. Increased contact with the guardian and liaison teacher may have improved student participation. Third, although interest was quite positive, overall, interest seemed to vary based on the kit and book. It seems likely that the lack of choice related to perceived personal interest may have undermined completion. Fourth, despite the researchers' anticipation of the role of the social justice-oriented prompts, the differences in the prompts did not lead to differences in students' responses. This suggests that the social justice-oriented trade books, as well as the STEM kits, were more influential than the prompts; that they were able to stimulate elements of culturally relevant pedagogy (Ladson-Billings, 1995; Morales-Doyle, 2017), including students' cultural competence and critical consciousness. Finally, students gave positive and encouraging comments, reflecting that the intervention positively impacted students' sense of capability and future career aspirations in STEM. The role models from the trade books seemed to resonate for many of the students (Blanchard et al., 2023; Clark et al., 2024).

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Exploring the Perspectives of Families Following Their At-Home STEM Tinkering Experiences

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This qualitative study explores the experiences and perceptions of nine families who participated in STEM Home Edition, a year-long at-home STEM learning program designed for middle school students and their families. The program aimed to foster STEM engagement and conceptual understanding through hands-on activities, including Circuit Scribe, Meccano robots, Germ Glo and Achoo! and Steve Spangler's Larry's Lab. Using the Learning Dimensions of Making & Tinkering framework (Bevan et al., 2017), this study analyzed family interactions across five dimensions, with a focus on Creativity & Self-Expression (LD4) and Social & Emotional Engagement (LD5). Data were collected from interviews and pre- and post-activity reflections with nine families. Findings revealed that Creativity & Self-Expression was the most often described Learning Dimension (45%), characterized by youth and adults expressing joy, constructing explanations, and setting personal goals. Social & Emotional Engagement followed (25%), emphasizing family members' perceptions of collaboration, confidence, and pride in the outcomes. Other Dimensions—Conceptual Understanding (15%), Initiative & Intentionality (12%), and Problem Solving & Critical Thinking (3%)—highlighted families' reflection on their ability to control variables, persist through challenges, and troubleshoot. The study also observed the demographic diversity of participants, with most families led by mothers and including a mix of racial/ethnic backgrounds and educational levels. These findings provide novel insights into at-home STEM engagement and underscore the potential of family-centered STEM programs to enhance learning, build confidence, and foster STEM identity. The study contributes to research on informal STEM education, offering practical insights for future program design and implementation.

Keywords: Out-of-school contexts, STEM education, Qualitative research

Importance Of Study

Engaging families in informal STEM learning fosters interest and participation in STEM fields (Dabney et al., 2016; Lin & Schunn, 2016; Roberts et al., 2018). Informal STEM activities, such as museum visits, zoo trips, and hands-on home experiments, enrich classroom learning and provide extended engagement opportunities (Roberts et al., 2018; Blanchard et al., 2020). Family involvement is also linked to improved academic outcomes for middle and high school students (Hill et al., 2018). However, parental engagement in STEM education presents challenges. Many parents face time constraints (Jeynes, 2006, 2010, 2012; Mapp et al., 2008) and barriers to school involvement (Bhargava & Witherspoon, 2015; Hill et al., 2018). As children enter adolescence, parents often step back to encourage independence (Hill et al., 2018). Yet, at-home STEM activities can increase students' motivation, confidence, and appreciation of STEM, similar to other informal learning experiences (Lin & Schunn, 2016). Encouraging parental participation in STEM at home can enhance students' engagement, knowledge acquisition, and career planning (Epstein, 1986).

Tinkering is commonly described in the literature as an interdisciplinary, inquiry-driven approach that integrates STEAM domains and emphasizes creativity, iteration, and problem solving, despite variation in how the term is defined. Vossoughi and Bevan (2014) characterize tinkering

as a mindset that spans making and engineering, highlighting experimentation, learning through failure, and iterative design. Tinkering often engages learners in open-ended exploration rather than predetermined outcomes and is most frequently studied in informal learning environments such as museums, camps, and afterschool programs.

Research demonstrates that tinkering can effectively support engagement with engineering concepts and practices. Marcus et al. (2021) found that family-based engineering design challenges fostered playful exploration and iterative testing, particularly when participants were provided with activity-specific guidance and access to testing stations. Similarly, Simpson et al. (2020) reported that elementary students in an informal afterschool STEM program demonstrated meaningful engagement with electricity and circuitry through hands-on tinkering projects. Although these activities aligned with NGSS expectations, the informal contexts afforded learners greater flexibility, time, and resources to enact science and engineering practices than is often possible in formal classroom settings. Together, these studies highlight tinkering's potential to support authentic STEM learning and family engagement in informal educational spaces.

This qualitative study examines the experiences of nine families participating in the STEM Home Edition program over ten months. This work extends previous work (Gutierrez et al., 2025) by detailing how these families interacted during STEM at-home activities. By exploring family reflections through interviews about their engagement in at-home STEM activities, this study provides insight into how informal STEM learning contributed to families' STEM engagement and development.

Conceptual Framework

The *Learning Dimensions of Making & Tinkering* framework (Bevan et al., 2017) served as a guide to document how families reflected on their participation in STEM activities at home. This framework consists of five key Learning Dimensions, as illustrated in Table 1. Multiple dimensions were often referenced simultaneously during family interviews, reflecting their interconnected and overlapping nature rather than existing as isolated or distinct categories. Initiative and Intentionality (LD1) captures evidence of self-directed learning, goal setting, and persistence. For this study, "organization of materials" was added to represent at-home activity contexts better. Problem Solving and Critical Thinking (LD2) includes experimenting with strategies, seeking assistance, and refining approaches; "building and assembly" was added to reflect hands-on construction practices. Conceptual Understanding (LD3) focuses on how participants generate explanations and use material properties to meet design goals. Creativity and Self-Expression (LD4) encompasses aesthetic responses, playful exploration, and novel uses of materials; "expressing negative emotions" was incorporated to capture affective responses observed in the data. Social and Emotional Engagement (LD5) reflects collaboration, mutual support, confidence building, and expressions of ownership.

Research Design And Research Question

This study used a qualitative study design (Creswell, 2013) to investigate the experiences of nine families who participated in at least three of the four at-home STEM activities. The after-school STEM Club students attended one of two rural, Title I middle schools in the southeastern US, and participated in a STEM Club at their school (Blanchard et al., 2023).

The research question for this study is: *How did families reflect on their tinkering experiences after an at-home STEM intervention?*

Table 1. The Learning Dimensions of Making & Tinkering (adapted from Bevan et al., 2017)

Dimension	Indicators
LD1: Initiative & Intentionality	a. Setting one's own goal b. Taking intellectual and creative risks c. Complexifying over time d. Persisting through failure e. Adjusting goals based on feedback f. Organizing materials*
LD2: Problem Solving & Critical Thinking	a. Troubleshooting through iterations b. Moving from trial-and-error to inquiry-focused refinement c. Developing work-arounds d. Seeking ideas, help, and expertise e. Building and/or assembly*
LD3: Conceptual Understanding	a. Controlling variables as projects complexify b. Constructing explanations c. Using analogies and metaphors d. Applying material properties to design
LD4: Creativity & Self-Expression	a. Responding aesthetically to materials b. Connecting projects to personal interests c. Playful exploration d. Expressing joy and delight e. Using materials in novel ways f. Expressing negative emotions*
LD5: Social & Emotional Engagement	a. Remixing or building on others' ideas b. Teaching and helping one another c. Collaborating in teams d. Developing confidence e. Expressing pride and ownership

Note: Indicators added by the authors are designated with an asterisk.

Methods

STEM Home Edition Program

The *STEM Home Edition program* (pseudonym) was implemented in the homes of students who were members of an ongoing after-school club and took place over one academic year. Each student began by bringing home a STEM kit to share with their family. Kits included STEM materials, snacks, activity instructions, career and post-secondary information, and pre/post-activity reflection prompts (Gutierrez, K. S. & Blanchard, M. R., 2018). The four activities were: 1) Circuit Scribe kit, 2) Meccano robot, 3) Germ Glo and *Achoo! The Most Interesting Book You'll Ever Read About Germs*, and 4) Steve Spangler's *Larry's Lab* (water-soluble polymers). Families kept the materials and received the next activity after submitting data. Up to four activities could be completed sequentially. At the program's end, families participated in interviews. Transcribed interview data totaled 82 pages and were coded using a priori categories

from the *Learning Dimensions of Making & Tinkering* framework in Atlas.ti, with additional codes for family context, such as "Family Dynamics" and "Family Relationship."

Participants

The demographic data reflect the diversity of families in the STEM Home Edition program. Most participants were White (5 families), followed by Black (3) and Multi-Racial (1). Slightly more were female (5) than male (4), with ages ranging from 11 to 13, and most (5) were 11 years old.

Mothers were the primary participants in eight families, with two families involving fathers and one with both parents actively engaged. Educational backgrounds varied: three adults held graduate degrees, three had undergraduate degrees, three had some college, and one had a high school diploma. Most families had one or two children involved, though one had four and another had three. This overview highlights the varied family contexts in the program.

Findings

Through the family interviews, the analysis of activity learning dimensions that was guided by the Learning Dimensions of Making & Tinkering framework, highlights the diverse ways participants engaged with STEM activities (see Table 2). *Creativity & Self-Expression* (LD4) was the most frequently observed dimension, accounting for 45% of codes (114 instances). For example, reflecting on the Circuit Scribe activity, the daughter from the Murphy family expressed, "*Well, it was very entertaining, and it - I thought it was really cool how, like, the electricity would flow through the little, like, parts where you draw on the paper. I thought that was really interesting.*" Reflecting on the Germ Glo activity, the mom from the Brown family said "I liked the germs one because I was amazed to see what was on our hands [...] it was amazing." This dimension reflects participants' joy, aesthetic responses, and creative use of materials. Key indicators included both youth and adults expressing joy (44 and 32 instances, respectively), youth constructing explanations (18 instances), and youth setting goals (13 instances).

Table 2. Percentages (and Frequencies) of the Learning Dimensions [and Indicators] of Making & Tinkering Reflected on During Family Interviews.

Activity	**Learning Dimensions**		**Most frequent indicators**
Family Interview	LD4: Creativity & Self Expression (114)	45%	Youth Expressing joy and delight (44)
	LD5: Social & Emotional Engagement (63)	25%	Adult Expressing joy and delight (32)
	LD2: Problem Solving & Critical Thinking (8)	3%	Youth constructing explanations (18)
	LD1: Initiative & Intentionality (31)	12%	Adult constructing explanations (16)
	LD3: Conceptual Understanding (38)	15%	Youth setting own goal (13)

Social & Emotional Engagement (LD5) was the second most prevalent dimension, comprising 25% of codes (63 instances). The dad from the Jones family reflected on the program saying, "*It enhanced my team-building skills, so that's what I can use later in life, more or less… that, and working with my son.*" This dimension highlights building confidence, teamwork, and pride in outcomes.

Other dimensions were less frequently observed but still enriched the learning experience. *Conceptual Understanding* (LD3), accounting for 15% of codes (38 instances), focused on controlling variables, constructing explanations, and connecting materials to achieve design goals. The mom from the Mueller family shared "*I had never heard the word polymer before, even though we had had the Orbeez, I didn't, again, read the directions that came with the Orbeez. I did not realize they were called polymers.*"

Initiative & Intentionality (LD1), representing 12% of codes (31 instances), highlighted goal-setting, persistence, and adapting plans. The son in the Wilson family noted, *"I learned a bit more about the jobs I'm interested in and a bit more about some of the jobs I'd rather not go for and still see how they're interesting to me sometimes too.*"

Problem Solving & Critical Thinking (LD2), the least observed dimension at 3% (8 instances), emphasized troubleshooting and creative workarounds. Reflecting on troubleshooting, the mom and daughter from the Baker family shared:

Daughter: *Circuits didn't really work.*

Mom: *Well, it took a little working with it and making sure to get it - to do things appropriately.*

These findings demonstrate how multiple dimensions often overlap, creating a rich, multifaceted learning environment where each dimension was evidenced at varying degrees of frequency.

Discussion

This study highlights the impact of family-centered STEM programs like STEM Home Edition in fostering engagement, learning, and confidence. Using the Learning Dimensions of Making & Tinkering framework (Bevan et al., 2017), findings reveal diverse family interactions with STEM activities. *Creativity & Self-Expression* emerged as the most prominent dimension, reflecting the joy and curiosity sparked by hands-on exploration. At-home STEM activities can enhance intrinsic motivation and creative problem-solving. *Social & Emotional Engagement*, the second most observed dimension, emphasizes collaboration, confidence-building, and emotional investment in STEM learning.

Less frequent but still significant, *Conceptual Understanding* and *Initiative & Intentionality* highlight the value of applying scientific concepts and persisting through challenges. The limited presence of *Problem Solving & Critical Thinking* suggests a need for more complex, iterative tasks within at-home programs.

Conclusions And Recommendations

These findings suggest several practical recommendations. Program designers should prioritize activities that integrate creativity, collaboration, and conceptual understanding to enhance engagement and learning. Providing resources to guide goal-setting and problem-solving may strengthen Initiative & Problem Solving. The program's demographic diversity underscores the need for culturally responsive design to ensure relevance across backgrounds. Lastly, involving families in STEM education fosters STEM identity and long-term interest. Schools and community organizations should adopt family-centered STEM models to connect informal and formal learning.

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Bridging Educational Landscapes – Out-of-School Learning in Biology and Its Complementarity with Formal Curricula

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Out-of-school education is considered to play a major role in teaching biological content and the acquisition of corresponding competencies. Still, the educational goals of out- of-school learning settings and their complementarity to those of school-based biology learning are almost unidentified. This research project is concerned with identifying the educational objectives used by out-of-school learning environments. In a qualitative case study, the out-of-school learning environments of a national STEM-cluster (N = 34) were analysed regarding their educational objectives concerning biology education. These objectives were ascertained through guided interviews with staff members of the environments and through the systematic collection and analysis of the educational materials of the learning environments. In addition, the similarities and differences between these and the educational objectives of school-based biology learning were identified. For this purpose, the collected educational objectives of out-of-school learning were compared with the educational objectives described in the national educational standards in biology by content analysis. The results of this study indicate that a common ground already exist between school-based and out-of-school biology learning within the STEM-cluster, particularly in developing competencies related to 'content knowledge' and 'decision-making'. However, the study also reveals untapped potential for further integration of school-based and out-of-school learning environments, which could enrich the biological education.

Keywords: Out-of-School Learning; Competencies; Complementarity

Theoretical Background

From the perspective of biology education, out-of-school learning environments are associated with numerous characteristics that support learning biology: Children and young people learn in diverse places, through various activities, and in different (social) constellations. They experience a real, practical connection to the subject matter and learn in an activity-based, independent way (Sauerborn & Brühne, 2020). The development of networked thinking and learning through multiple sensory channels is also at the core of out-of-school learning environments (Sauerborn & Brühne, 2020). According to Sauerborn and Brühne (2020), these aspects contribute to the long-term retention of acquired skills. They also prevent diminishing interest in scientific topics: Numerous studies on the effectiveness of out-of-school learning environments have shown that they can positively influence motivation and interest in science (overview in Bell et al., 2009). However, in the public's perception, schools are at the center of education. This perspective is also reflected in the research landscape, where school-based learning is studied far more frequently than out-of-school learning environments and is often clearly separated from learning outside of school. However, Birmingham and Calabrese Barton (2014) outlined the lack of a clear distinction between school and out-of-school learning: learners constantly cross the boundaries between learning in the context of school and situations of learning experienced in everyday life or out-of-school contexts – regardless of the place they are in.

For this reason, the consensus on a sharp differentiation of learning sites is shifting to a discourse on learning in which the boundaries between formal and informal education and between different educational institutions are blurred (Dierking & Tal, 2014). Bell and colleagues (2009) postulate that most people build their understanding of science throughout their lives by gathering and

processing information from many places and contexts for a variety of reasons. Learning in general, and science learning in particular, according to this view, occurs over time through a person's countless experiences, including learning opportunities within the context of school or at out-of-school learning environments (Dierking & Tal, 2014).

Approaches to conceptualise school-based and out-of-school biology learning in a complementary way remain largely superficial (e.g., Favre & Metzger, 2019). This is partly due to the fact that the design of out-of-school learning environments often lacks a deliberate connection between the educational objectives of these environments and those of formal school-based learning, preventing the full potential of these visits from being realized (Eshach, 2007). Furthermore, the integration of both learning environments could be hindered by a lack of clarity regarding the educational goals of out-of-school learning environments, which – unlike school-based educational institutions – do not have curricular guidelines.

Key Objectives

Based on the state of research, this study aims at giving a frame for a common perspective of school-based and out-of-school biology learning. Therefore, the study focuses on the comparison of the educational objectives of school-based learning with the educational objectives of didactically designed out-of-school learning environments. Since out-of-school learning environments do not follow curricular guidelines, their educational goals must first be identified. For this purpose, out-of-school learning environments of a national STEM-cluster are examined. Only learning sites that stated to teach biological contents and competencies are included in the study. Through a content-analytical comparison of the surveyed out-of-school educational objectives with those of school-based biology learning, already existing correlations as well as 'white spots' regarding complementarity and thus opportunities for stronger interconnections can be identified. This comparison is made against the background of the following questions:

1. What are the similarities and differences between the educational objectives of out-of-school and school-based biology learning?
2. To what extent do possible differences result in synergistic potential in the sense of a stronger interconnection of the learning environments?

Research Design

In the region of the STEM-cluster, 34 out-of-school learning environments were identified that (among other things) aim to address biological competencies. They can be assigned to the learning environment categories defined by Möller and colleagues (2023) (see Table 1), i.e., the learning environments can be distinguished in various settings – from nature parks to organic farms to environmental education centres – where biological topics are addressed in an engaging and experiential way.

The educational goals of the learning environments were elicited through guided interviews (Helfferich, 2011) with one site staff each. The interviews included five guiding questions that focused on the framework, the content, and the educational objectives of the environments. Each guiding question was further divided into two to six sub-questions to gain deeper insights. To gain a comprehensive understanding of the educational objectives of the learning sites, the guiding questions were formulated as narrative prompts. The interview questions had been piloted in spring 2023. Data collection for the main study was conducted from April 2023 to July 2024. The N=34 interviews ranged in duration from 28 to 46 minutes. In addition to the interviews, a systematic screening of existing educational materials (e.g., exhibition materials)

from the out-of-school learning environments was conducted to further identify and analyse their educational objectives.

Table 1. Learning environment categories with corresponding sample sizes.

Categories of learning environments	Number of environments in the sample
Zoos/Wildlife Parks	3
Nature Parks/Gardens and Protected Areas	6
Museums	5
Environmental Education and Experience Centres	7
(Agricultural) Farms	10
Youth Centres or Clubs	3

The content analysis of the interviews and materials of the learning environments is based on the qualitative content analysis method according to Kuckartz and Rädiker (2023). Therefore, a deductive category system was established based on the educational objectives outlined in the national educational standards for school-based biology education (Sekretariat der KMK, 2005). These objectives are divided into four competence-areas: 'content knowledge', 'procedural and epistemic knowledge', 'communication and interaction' and 'decision-making', which also represent the main categories of the deductive category system. The educational goals of the out-of-school learning environments – those identified through interviews as well as those obtained through the systematic screening of educational materials – were classified within the deductive category system. Educational goals of the out-of-school learning environments that could not be assigned to the category system are included in the analysis as inductive categories. As a result, the deductive and inductive categories contain the educational goals of school-based and out-of-school learning in the region under study.

The similarities and differences between educational objectives of out-of-school and school-based learning can then be taken from the category system: Filled deductive categories indicate a pre-existing match of the two types of learning sites. Unfilled deductive categories and categories inductively generated from the material of the out-of-school learning environments show where the educational goals of both environments (so far) diverge. Against the backdrop of a common perspective, these differences will be discussed in terms of the potential for greater intertwining.

Findings

Results show that the educational objectives of school-based and out-of-school learning in the region predominantly overlap in terms of 'content knowledge' and 'decision-making' competencies. Regarding other competence-areas, the fit is less pronounced: the learning environments pursue different learning objectives, particularly when it comes to developing skills for acquiring 'procedural and epistemic knowledge'. Many out-of-school learning environments focus on original encounters and general experiences of nature, for example through criteria-based observation of living nature. These competencies are not pursued by the governmental educational standards of school-based learning. The competence-area 'communication' also

shows less overlap. This is due to the fact that only a small proportion of communication-related competencies of school-based biology learning and also a small proportion of own communication-related competencies are pursued by the out-of-school learning environments. This area of competence is underrepresented at out-of-school learning environments in the region studied. In addition to competencies that can be assigned to the competence-areas of biology learning at school, the out-of-school learning environments also address competencies that cannot be assigned to any of the competence-areas of school-based biology learning. These include

- taking responsibility for living organisms,
- establishing connections between biological phenomena and other (scientific) disciplines,
- perceiving biological phenomena with all senses,
- gaining a (practical) understanding of biological phenomena through learning in real-world contexts,
- articulating the relevance of biological phenomena for one's own personal life context, and
- developing environmental awareness and sensitivity.

These additional competencies therefore mark a further point of divergence from school-based biology learning.

Conclusion

At its core, this study challenges the dichotomy between school-based and out-of-school education and argues for a more integrated approach. The limited overlaps between school-based and out-of-school learning regarding the competence areas 'procedural and epistemic knowledge' and 'communication' open up potential for synergies, as different approaches to develop competencies can be combined.

Beyond these partially shared competence areas, the study highlights that out-of-school learning environments address a range of independent competencies that are not explicitly covered by the competence framework of school-based biology education. These competencies, which often emerge from experiential, context-based, and sensory-rich learning situations, represent an additional potential for synergy. Integrating such competencies into school-based learning processes could contribute to a broader understanding of biology education that extends beyond curricular knowledge acquisition and supports more holistic learning processes.

By recognizing and leveraging the multiple strengths of both school-based and especially out-of-school learning, educators can provide a more comprehensive and engaging educational experience. In doing so, they can foster a generation of learners who not only have a deep understanding of biological concepts but also develop a profound connection to the natural world. As we move forward, it is essential to recognize the similarities and differences and explore their potential for collaboration to shape a truly effective and impactful biology learning.

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Part 12 / Strand 12

Equity, Diversity And Identity In Science Education

Co-editors: *Wonyong Park & Katerina Pia Günter*

Part 12 / Strand 12 Equity, Diversity And Identity In Science Education

Socio-political, sociocultural, multicultural, multilingual, multi-modal, intersectional, racial/ethnic, equity, critical, feminist, and gender studies, as well as special needs in science education. Proposals that include theories, methods, and practices related to ways-of-being and ways-of-knowing in science education and through an array of onto-epistemological perspectives, ideas, theoretical, and methodological approaches build on and perhaps exceed identity in inter-, multi- and transdisciplinary ways. Inviting critical examination of identities as multiple and situated in various systems of power and privilege to afford complex understandings of educational opportunities related to access and achievement.

Sub-themes:

1) Addressing Gender and Racial Equity in Science Education
2) Multicultural and Multilingual Approaches in Science Teaching
3) Inclusive Practices for Students with Special Needs in Science
4) Intersectionality and Identity in Science Education
5) Critical Pedagogy and Social Justice in Science Education

Contents

Strand 12: Equity, Diversity And Identity In Science Education 1087

Design And Validation Of An Instrument For Analysing Gender Perspectives In STEM Teaching Practices: The WOUMAP Questionnaire 1090

The Debate on the Race-Gender-Class Triad at The Main Science Education Research Event in Brazil, from 1997 to 2023 1096

Addressing Girls In Out-Of-School STEM Labs 1104

The Influence Of School Experiences In The Construction Of A Scientific Identity – A Case Study With Brazilian Transgender Persons 1109

Science Capital Of Brazilian Students From The Periphery Of Rio De Janeiro: Correlations Between Gender, Ethnicity And Parents' Educational Level 1119

Inclusive Movement: Rethinking Physical Engagement In Science Classrooms 1127

Validation Of A Professional Science Identity Scale For Higher Education Students Of Chemistry 1132

Examining Cultural Influences On The Development Of Classification Among Indigenous Students 1137

Positioning Towards Science From An Identity Perspective: Results Of An Interview Study With Pupils In Their Initial Science Lessons 1146

Identifying And Understanding Factors Influencing Students' Decisions Regarding STEM Education Pathways – First Findings 1153

Queer In STEM Queering STEM: The Story And Insights Of A Trans, Ace, White Woman In Chemical Engineering 1163

A Multiple Case Study Of Translanguaging And Systemic Functional Linguistics In K-12 Science Education 1168

Exploring STEM Identity Development In Early Science Education In Germany: Gender Differences And The Impact Of Science Capital 1174

Deconstructing Stereotypes: A Critical Approach To Indigenous Knowledge In Chemistry Education 1181

How Families' Everyday Engagements Hold Potential For Cultivating Students' Science Capital And Align With School Science 1191

Barriers In The Planning Phase Of Open Inquiry-Based Learning: Analysis From The Perspective Of Inclusive Science Education 1199

The Challenges Of Inclusive Science Education From Teachers' Perspectives 1207

Youth's Environmental Attitudes And Use Of Digital Media And Social Networks: A Comparative Exploration From Seven Spanish-Speaking Countries 1216

Strand 12: Equity, Diversity And Identity In Science Education

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Equity, diversity and identity are central to science education, shaping who is recognized as a legitimate participant in science, whose knowledge is valued, and who can imagine scientific futures. Research on science identity, recognition and Science Capital shows that participation is mediated not only by attainment or interest, but also by social relations, institutional cultures and wider systemic inequalities (Archer et al., 2015; Carlone & Johnson, 2007; Hughes et al., 2021; Danielsson et al., 2023; Dou & Cian, 2022). At the same time, expanding work on science identities has highlighted the importance of recognizing the complex, dynamic and socially situated nature of identity formation across contexts and over time (MacLeod & Avraamidou, 2025), foregrounding how identities are continuously negotiated within educational systems and broader sociocultural structures. An identity-focused perspective therefore invites science educators in Europe and across the world to examine how curricula, pedagogies, assessments and learning environments can (re)produce exclusion, but also how they can open more just and meaningful forms of participation (Avraamidou, 2020).

The ESERA 2025 proceedings in Strand 12 (Equity, Diversity and Identity in Science Education) explore contemporary issues in science and STEM education across diverse contexts, disciplines, and educational levels. Covering Indigenous knowledge systems, STEM, physics, science education research, and teacher education, the works address learners from middle elementary to higher education, as well as pre-service teachers, in-service teachers, and teacher educators. Together, the proceedings highlight science education as a culturally and socially embedded practice and emphasize the need for inclusive, context sensitive approaches that connect learners' experiences with scientific knowledge. The works reflect a broad international scope across multiple continents, including authors affiliated with institutions in Europe with Austria (1), Denmark (1), Germany (7), Greece (1), the Netherlands (1), Spain (2), Switzerland (1), and the United Kingdom (1), Asia with Israel (1), Singapore (1), and Taiwan (1), North America with the United States (1), and South America with Brazil (4).

The contributions in this strand address science and STEM education through three closely connected perspectives: 1) STEM and science identity formation, 2) equity and intersectionality, and 3) sociocultural influences. Across the papers, identity emerges as a dynamic process shaped by subject experiences, gender, Science Capital, and broader epistemological positions, while persistent inequities highlight how access, participation, and belonging are unevenly distributed. Learning is shown to be deeply embedded in sociocultural contexts, including family practices, language use, and Indigenous knowledge systems, which often remain underrecognized in formal science and STEM education. These perspectives converge in a shared concern with transforming educational practices, as studies on inquiry and teaching highlight the need to move beyond deficit views and address systemic and structural barriers. Together, the three themes point to a common pattern: participation in science is co-constructed through the interplay of identity, culture, and educational structures, calling for more inclusive, context-sensitive approaches to science education. However, they also display the diversification of perspectives on Equity, Diversity and Identity in Science Education.

STEM/Science Identity Formation and Trajectories

These contributions collectively frame science and STEM identities as contextually situated, evolving and unevenly supported across educational settings. Rather than treating participation as a matter of stable preference or ability, they show how learners negotiate subject-specific identifications, broader STEM self-concepts, environmental orientations, digital practices, and ideas about science in relation to school biography, gender, Science Capital and cultural knowledge systems (Bochert et al., 574; Manassero-Mas & Vázquez-Alonso, 1601; Birner et al., 716; Lisa-Marie Christ et al., 659; Bub et al., 830). Across the submissions, identity formation appears as a dynamic process shaped by institutional structures and epistemic norms: students may move towards or away from physics, chemistry or STEM more broadly as they encounter particular classroom experiences, disciplinary images and recognition opportunities. Several papers also point to the need for more inclusive and longitudinal approaches, both methodologically and pedagogically, including validated identity measures, narrative and interview-based work, and decolonial models that challenge the marginalization of Indigenous knowledge in science education (Raupp & Vanuchi, 901).

Equity, Diversity, Inclusion, and Intersectionality

These contributions collectively examine how inequality and inclusion in science education are produced through intersecting social, institutional, spatial and epistemic conditions. Rather than treating disadvantage as a single-axis problem, they show how race, gender, class, geography, disability, sexuality, gender identity and Science Capital shape learners' participation, recognition and sense of belonging in STEM. Submissions highlight the need for more intersectional and context-sensitive analyses, including work on how inequality is represented in science education research, how teacher educators and pre-service teachers understand gender equality, and how students' STEM motivations differ across social and geographic contexts (Pontes Silva & Franco dos Santos, 84; García-Ruiz et al., 40; Duek et al., 512; Silva, Teixeira, & Santos, 474).

Across the studies, inclusion is framed not only as a matter of access, but as a question of embodied participation, institutional responsiveness and everyday classroom practice. Contributions on physical ability, open inquiry, transgender students' experiences, and trans trajectories in chemical engineering show that barriers often arise from taken-for-granted norms about bodies, methods, identities and belonging, rather than from learners' deficits (Müller et al., 551; Abels et al., 1749; Cordeiro Lopes Fonte & Mendes da Silva, 239; Marosi et al., 784). Others caution that ostensibly inclusive spaces, such as out-of-school STEM laboratories, may reproduce gendered hierarchies through implicit pedagogical assumptions and differential forms of address (Gross & Abels, 194). Taken together, these submissions suggest that meaningful inclusion requires coordinated work across curriculum, pedagogy, teacher education, institutional culture and policy, particularly because teachers may support inclusive principles while still feeling underprepared to enact them in practice (Pannullo et al., 1751).

Sociocultural and Community Influences on STEM Learning

These contributions foreground sociocultural, linguistic and familial resources as central to science learning, challenging narrow views of what counts as legitimate scientific knowledge and participation. Across multicultural, multilingual and family contexts, they show that learners' sense-making is shaped by culturally embedded classification practices, translanguaging and everyday experiences that often sit outside formal school science. Indigenous Tao learners' biological classifications, for example, combine increasing taxonomic precision with ecological and cultural knowledge, challenging deficit views of Indigenous learners (Ge et al., 617).

Similarly, translanguaging among English learners appears as a collaborative resource for scientific reasoning and meaning making rather than a barrier to instruction (Barron et al., 788). Family activities also generate rich forms of Science Capital, but these sensory and meaningful experiences are not always recognized by schools (Nielsen et al., 1428). Together, the submissions argue for science education that connects disciplinary learning with students' cultural, linguistic and everyday lives.

The contributions in this strand offer rich and multifaceted insights into science identity, equity, diversity, and in particular the sociocultural dimensions of learning. Further, they point directly and indirectly to areas that remain less developed within current research and/or its communication in the proceedings of ESERA Strand 12. Much of the work continues to focus on how learners navigate participation within existing structures of science education, while fewer contributions explicitly interrogate how those structures themselves define the boundaries of legitimate knowledge, identity, and participation. Questions of epistemic justice, whose knowledge systems shape science education, how scientific norms are historically and culturally constituted, and how dominant epistemologies might be re-imagined, remain comparatively invisible. While intersectional and sociocultural perspectives are increasingly present, there are potentials and openings to more fully engage with science education as part of broader socio-political and historical formations, including colonial and global knowledge hierarchies that continue to shape what counts as science. Moving forward, we suggest the value of expanding science identity research beyond questions of access and recognition towards inquiries that also consider transformation and possible futures: not only how diverse learners come to see themselves as scientists, but how science education itself might be reconfigured when multiple ways of knowing, being, and valuing are taken as constitutive rather than supplementary, transgressing narrow and often deficit-oriented and neoliberal ideas of equity and diversity towards collaborative, collective, and community-oriented social and environmental justice.

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Design And Validation Of An Instrument For Analysing Gender Perspectives In STEM Teaching Practices: The WOUMAP Questionnaire

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In the changing world in which we find ourselves, there is a need to form a citizenry with a background in STEM (Science, Technology, Engineering, and Mathematics) related areas, who develop skills and competencies needed to make reasoned, well-founded decisions about problems that have not yet arisen. However, despite the emphasis on promoting curricular integrated STEM education, a gender gap persists, with women underrepresented in STEM fields. This imbalance, which has significant implications for equity and progress, limits innovation and social development, perpetuates labour inequality, and generates biased technological solutions by excluding diverse perspectives, resulting in less female representation that hinders equity and progress. It begins to manifest itself in Early Childhood Education, being therefore essential to prepare teachers at different educational levels in this regard, by understanding their initial perceptions of teaching science and technology from a gender perspective and delving into the stereotypes they hold based on their previous experiences. Consequently, this study describes the validation by experts of a structured questionnaire designed to examine teacher trainers' and pre-service teachers' perceptions concerning promoting gender equality in STEM areas. The validation was carried out through a panel of experts in science education, guaranteeing the relevance and reliability of the instrument, composed of 15 items distributed in four main categories related to perception and awareness of gender equality in STEM, practices and initiatives for the promotion of equity, identification and impact of female references in STEM and experiences and improvement proposals. Implementing the validated questionnaire will contribute to understanding current practices in STEM education, providing a comprehensive view of how teachers address the gender perspective in their teaching, their knowledge of leading women in the field, and the strategies they consider to promote gender equality.

Keywords: Pre-service teachers, Gender Awareness, STEM education

Theoretical Framework

International organisations have increasingly prioritised educational equity within STEM (Science, Technology, Engineering and Mathematics) disciplines, with gender-responsive pedagogy emerging as a critical policy concern (European Commission, 2020; OECD, 2022), aiming to deconstruct gender-normative assumptions in developing inclusive STEM education systems. However, there is a persistent STEM gender-bias strongly influenced by internalised gender stereotypes, social expectations, and a lack of scientific references (Hughes et al., 2020), that culminates in an imbalance in shaping professional trajectories, with overrepresentation of women in health-related and well-being areas, as opposed to underrepresentation in the STEM areas (World Economic Forum, 2023).

Research has continuously demonstrated that such disparity originates from the early stages of compulsory education (Brussino and McBrient, 2022), with female students developing a gender-based self-perception and competency-related doubts that affect their motivation, expectations,

intellectual aptitudes, and ultimately, their education and professional career choices towards strong social orientation careers (Cimpian et al., 2020; Evagorou et al., 2024).

Within this scenario, schools and educational actors emerged as key agents in the socialisation process of youth, developing an active role in disrupting gender stereotypes reproduction, as defined within the objectives of the STEM Alliance for Female Talent (Grañeras et al., 2022), which proposes goals such as making women visible in scientific-technological fields. This emphasis on the school's role should make educators, researchers, and policymakers feel the importance of their work in challenging gender stereotypes (Brussino and McBrient, 2022).

Multiple publications demonstrate that exposure to inspiring role models is crucial for fostering student commitment to STEM disciplines, an effect that is especially pronounced among women exposed to role models of the same gender. However, this representation is far from being adequately gender inclusive (González-Pérez et al. 2020). The need for more gender-inclusive role models is urgent, and it is crucial that pre-service teachers develop an adequate understanding of science and technology to challenge the stereotypes that persist in curricula and within the teaching community.

Aims And Research Questions

Considering the relevance of the exposure to women role models in STEM fields throughout the different education stages, we understand that it is necessary to research and analyse the perception that pre-service teachers and their teacher trainers of the degrees of Early Childhood Education, Primary Education and the scientific-technical specialities of the Master in Education have about the visibility of women in STEM areas. We hypothesise that the teacher's reflection on the gender gap in STEM areas will increase knowledge across all educational strata, fostering a concept of inclusive science, and an appreciation of female talent from an early age. Consequently, we aimed to design a questionnaire to address the following research question:

- How do we design and validate an instrument that evaluates teacher trainers' and pre-service teachers' perceptions and practices about promoting gender equality in STEM disciplines?

Methodology

Questionnaire Design

We designed the WOUMAP questionnaire following a thorough review of the relevant literature and discussions with the co-authors of this research. The first draft consisted of 15 items, which combined open-ended and 5-point Likert-type scale questions. The items were organised into four main categories: perception and awareness of gender equality in STEM (items I1, I2, I4 and I9), practices and initiatives for the promotion of equity (items I5-I9), identification and impact of female references in STEM (items I10-I15) and experiences and improvement proposals (items I3 and I11). Given our target participants, we elaborated two equivalent versions of the questionnaire, one for teacher trainers and another for pre-service teachers.

Validation Process

We proceeded with instrument validation using a digital form in *Google Forms*. Since participation in the validation process required the identification of experts, thereby implying the processing of personal data, we followed the guidelines on the Protection of Personal Data and Guarantee of Digital Rights and obtained with the approval of the Ethics Committee of the University of Málaga (reference no. 96-2023-H).

The form briefly introduced the objectives and context of the research, establishing the guidelines for completing the review. The first block included some demographic questions to characterise the expert. Next, the second block presented the 15 items, along with an explanation of the associated research objective. For review, we asked the panel to indicate the degree of adequacy of each item to the corresponding objective on a four-point Likert-type scale (1: very low, 2: low, 3: high and 4: very high), as well as the justification of the item's degree of adequacy chosen and possible comments and suggestions for improvement to the item.

Data Analysis

We carried out the analysis in accordance with the nature of the data collected with the validation questionnaire. Hence, we used the R-based software JAMOVI (version 2.3.21) to analyse the quantitative data, examining the distribution of scores for each question and providing the frequency percentages, the mean (*M*) and standard deviation (*SD*) as interpretive values. We also calculated the Content Validity Index (CVI) for each item (I-CVI) and for the scale as a whole (S-CVI), as well as the exact binomial test (*p*), which represents the probability of obtaining the observed level of agreement or higher by chance. The I-CVI was calculated as the number of experts who gave a rating with a high degree of agreement (values of 3 and 4 on the 4-point Likert scale) divided by the total number of panel members, considering acceptable values equal or greater than 0.80 and as statistically significant results, coefficient p values less than 0.05. The S-CVI was calculated as the average, calculated as the sum of all the I-CVI of the scale divided by the number of items (S-CVI/Ave), with a threshold of 0.90 or higher being considered excellent.

At the same time, we assessed the consistency and reliability of the ratings given by each evaluator on the panel by calculating the Fleiss' *kappa* statistic, which analyses the agreement between the evaluations of the different people on the panel and, unlike the CVI, considers the agreement that is produced by chance (Fleiss et al., 2003). As in the calculation of the CVI, given that the interest was in distinguishing between the degree of general agreement and disagreement, the analysis was simplified by dichotomising the data, treating values of 3 and 4 as "agreement" and values of 1 and 2 as "disagreement".

On the other hand, the comments recorded as qualitative data were pooled for evaluation of modifications or deletions to the valued item.

Findings

The S-CVI/Ave for the entire questionnaire was 0.94 in the teacher trainers' version. The I-CVI scores ranged from 0.78 to 1.00 (Table 1). Except for I2, the I-CVI scores ranged between 0.89 and 1.00 (Table 1), and 8 of the 15 items reached the maximum level, with statistically significant *p*-values in all cases ($p < 0.05$). Item I2, which had the lowest threshold (0.78), was carefully reviewed, modified, or eliminated in accordance with the panel's comments. In addition, the Fleiss' *kappa* statistic was calculated, obtaining a value of $K = 0.89$ (standard error = 0.04, 95% CI = 0.82 - 0.96, $p < 0.01$), which represents a degree of substantial agreement of the instrument (values between 0.81 and 1.00) (Fleiss et al., 2003). We observed similar results for the pre-service teachers' version, with an S-CVI/Ave of 0.95 and the same I-CVI scores distribution. Only item I3 presented an unacceptable value (0.78), which was also reviewed. Fleiss' *kappa* statistic value was $K = 0.91$ (standard error = 0.08, 95% CI = 0.75 – 1.00, $p < 0.01$).

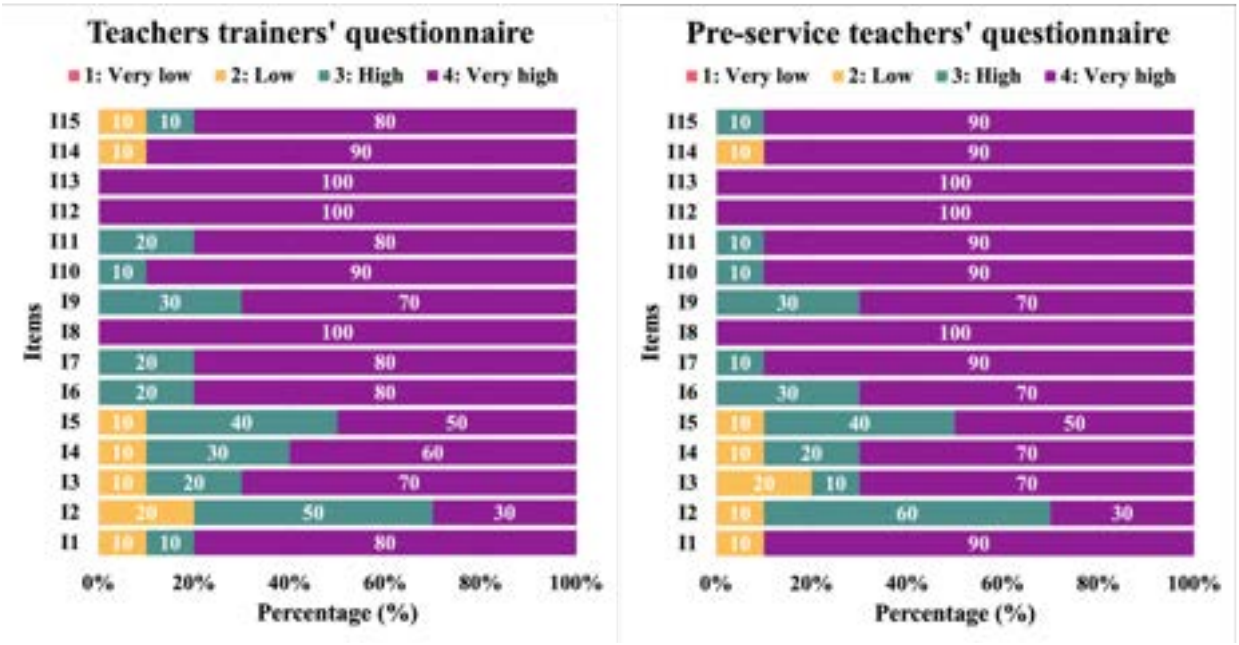
Figure 1 shows the results of the percentage of frequency obtained for items I1-I15 on teacher trainers' and pre-service teachers' versions. We observed a favourable assessment in all cases, with the sum of "high" and "very high" percentages exceeding 80% and mean values above 3.1 across all items. As indicated, I2 and I3 in the teachers' and students' questionnaires, respectively, which had the lowest mean and I-CVI values, were revised based on the qualitative assessment.

Table 1. Code, Content Validity Index (I-CVI), Mean (M), and Standard Deviation (SD) for each Item.

	Teacher trainers' version				Pre-service teachers' version			
Item	**I-VCI**	***p***	***M***	***SD***	**I-VCI**	***p***	***M***	***SD***
I1	0.89	0.01	3.70	0.67	0.89	0.02	3.80	0.63
I2	0.78	0.06	3.10	0.74	0.89	0.02	3.20	0.63
I3	0.89	0.01	3.60	0.70	0.78	0.04	3.50	0.85
I4	0.89	0.01	3.50	0.71	0.89	0.02	3.60	0.70
I5	0.89	0.01	3.40	0.70	0.89	0.02	3.40	0.70
I6	1.00	0.00	3.80	0.42	1.00	0.00	3.70	0.48
I7	1.00	0.00	3.80	0.42	1.00	0.00	3.90	0.32
I8	1.00	0.00	4.00	0.00	1.00	0.00	4.00	0.00
I9	1.00	0.00	3.70	0.48	1.00	0.00	3.70	0.48
I10	1.00	0.00	3.90	0.32	1.00	0.00	3.90	0.32
I11	1.00	0.00	3.80	0.42	1.00	0.00	3.90	0.32
I12	1.00	0.00	4.00	0.00	1.00	0.00	4.00	0.00
I13	1.00	0.00	4.00	0.00	1.00	0.00	4.00	0.00
I14	0.89	0.01	3.80	0.63	0.89	0.02	3.80	0.63
I15	0.89	0.01	3.70	0.67	1.00	0.00	3.90	0.32

I-CVI: Item content validity index; *p:* exact binomial test

Figure 1. Results of the Quantitative Validation on the Items I1-I15 for Teacher Trainers' and Pre-service Teachers' Questionnaire.



Thus, the final validated questionnaire consisted of 15 items, including questions on a 5-point Likert scale and open-ended responses, with summarised and general statements for the teacher trainers' and pre-service teachers' versions shown in Figure 2.

Conclusions And Implications

This work presents an *ad hoc* research instrument designed for teacher trainers and pre-service teachers in Early Childhood Education, Primary Education, and the scientific-technical areas of Secondary Education. The WOUMAP questionnaire would allow us to investigate these teachers' perceptions about the visibility of women in STEM areas and the gender gap they identify in their teaching practice.

Figure 2. Simplified Statements of the WOUMAP Questionnaire Items.

PERCEPTION AND AWARENESS OF GENDER EQUALITY IN STEM	EXPERIENCES AND IMPROVEMENT PROPOSALS
I1. To what extent do you think there are stereotypes and barriers that can hinder the interest of students in STEM careers (related to science, technology, engineering and mathematics? What do you consider those stereotypes and barriers to be? **I2.** To what degree do you think dedication to a career in STEM areas is compatible with personal balance and/or familiar balance? **I4.** To what degree do you consider that the gender perspective is adequately represented in the training of STEM areas? **I9.** To what extent do you think women are adequately represented in STEM fields?	**I3.** Could you describe if you have experienced support, empowerment or an increase in confidence during your development in teaching-learning in STEM areas? If so, what has this support been like, from whom, and how do you think it can or has had an impact on your professional career? **I11.** What actions or changes would you propose to increase the presence and visibility of leading women in STEM education?
PRACTICES AND INITIATIVE FOR THE PROMOTION OF EQUITY	**FEMALE REFERENCES IN STEM: IDENTIFICATION AND IMPACT**
I5. In the subjects of the degree or master's degree that you are teaching/ studying, to what degree is a gender perspective incorporated or is gender equality explicitly promoted in the teaching of STEM subjects? **I6.** In the subjects of the degree or master's degree that you teach/study what type of activities are carried out to promote the visibility of women in STEM disciplines (Activities aimed at emphasizing the achievements of women in my area/Mentoring programs/Inclusive curriculum/Others) **I7.** What type of initiatives or programs aimed at promoting the visibility of women in STEM disciplines do you know of? **I8.** Indicate how frequently the following actions are shown or discussed in the subjects of the degree or master's degree that you teach/study: • Science/Engineering as a human product built jointly by men and women • Poor representation of women in science/engineering • Current and relevant women close to science/engineering • Contributions from women relevant to science/engineering • Social and personal context of women relevant to science/engineering • Scientists/engineers invited to give a talk on the subject • Reflection that it is not necessary to have extraordinary abilities to dedicate yourself to science/engineering • Physical and geographic diversity of people who do science/engineering	**I10.** Could you mention three qualities or characteristics that you consider essential for a female scientist and/or engineer to become a reference or role model in these disciplines? **I12.** Make a list of three women scientists or engineers you know, identifying any particular discovery or contribution to their field. **I13.** How did you find out about these three women? **I14.** To what extent has knowledge about any of the women you have referenced influenced your interest in STEM areas? **I15.** Describe how that influence has been on your professional career.

After a rigorous validation process by a panel of experts in Science Education, statistics were calculated to assess the validity of the content (CVI) and the agreement among the panel's evaluations (Fleiss' *kappa*), yielding satisfactory results in both cases. These results, supported by the analysis of the qualitative responses provided by the evaluators concerning each item analysed, have generated a final questionnaire comprised of 15 items of combined typology (Likert scale and open response), offering an efficient tool to deepen the vision and commitment that teacher trainers and pre-service teachers have with respect to the practice of inclusive teaching, and thus being able to identify successful strategies for addressing the gender perspective at all levels of education.

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ESERA 2025 Copenhagen

The Debate on the Race-Gender-Class Triad at The Main Science Education Research Event in Brazil, from 1997 to 2023

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The history of science education in Brazil is permeated by domination and exploitation based on class, race, and gender. Thus, aiming to present an analysis of how the race-gender-class triad has been debated in science education in Brazil, we conducted a text search in the proceedings of the main science education research event in the country, the National Science Education Meeting (ENPEC), and analysed the theoretical frameworks underlying the articulation between these three categories in the works found. The debate involving race-gender-class in this field of research still treats the elements of this triad separately, as if they were independent of one another and not as part of the Brazilian socio-historical structure. This result reveals a deficiency in the way the Brazilian context of science education is treated in academia, an issue that must be overcome so that we can develop a fully emancipatory science education.

Keywords: race, gender, social justice

Introduction

Comprehending the historical development of science education in Brazil must involve understanding racism, class struggle and gender issues in the country, which permeate the entire history of Latin America. That is because it was the unit colonialism-capitalism-racism that structured all the development of Brazilian society (Santos, 2024), including science education. As Delizoicov (2004) points out, it is necessary to do the "historical recovery of science teaching" (p. 148) in Brazil, in a broad and multidisciplinary way.

Before entering science education history, it is important to remember the racist history of science, which used its social prestige to justify the inferiorisation and exploitation of black people, through craniology and phrenology, for example (Santos, 2024). Science, as a social product, has also been utilized to discriminate against women and, in some areas, still presents sexist views of the "feminine", associating it with hysteria, weakness and inability to use logic and reason, as it was in the beginning of hysteria history (Schmitz, 2021).

According to Santos and Galletti (2023), science education in Brazil began in the 16th century with Jesuit education developed from a scholastic perspective with the purpose of catechizing, indoctrinating and acculturating the native peoples of the "New World". In the 19th century, intending to educate the bourgeoisie children of the Brazilian landowning oligarchy, scientific education gained new nuances and a place of importance (Santos & Galletti, 2023). However, it was only from 1950 onwards, following a global trend, that scientific education became institutionalized and was officially included in the country's educational legislation, albeit of a professionalizing nature, seeking to respond to historical demands for industrialization and the enhancement of study and research centers (Santos & Galletti, 2023). Since the 1970s, during the military dictatorship in Brazil, questions about the neutrality of science, technological determinism, and scientific production risks arose and discussions have included not only what or how to teach, but also the subjects (who) and the purposes (for what). In this sense, since the political reopening and the efforts of organized political movements, issues of class, race, and gender have occupied the research and practice agenda in science education.

Thus, this paper's objective is to present an analysis of how the race-gender-class triad has been debated in science education in Brazil. We intend to answer the following question: how has the debate on the race-gender-class triad been treated in the field of science education in Brazil? We hope the answer can help us identify how these three categories are present in this area of education, how they are articulated, and how they indicate paths for developing a fully emancipatory education.

Theoretical Frame Of Reference

Considering that Brazilian science education was developed based on a society that excludes people who do not fit the universal subject model, the white man (Souza, 2020), it is necessary to understand the categories of race, class and gender as a unit in science education research. Addressing this triad requires a complex analysis, which comprehends the implications of these three elements together and, in this case, within the specificities of the concrete Brazilian reality. According to Kosik (1976), concrete reality takes in consideration what is beyond appearance, beyond the superficial and the immediate, a reality dependent on its socio-historical processes.

The dissociation of the three categories is reflected in science teaching, from the incipient representation of black women as members of the scientific class in textbooks (Silvério & Verrangia, 2021; Skumra et al., 2020) to the apparent difficulty (or resistance) that science teachers might have in complying with current educational legislation, including the teaching of Afro-Brazilian and Indigenous history and culture (*Lei [Law] 10.639*, 2003; *Lei [Law] 11.645*, 2008) in their pedagogical activities.

In this sense, we turn to Lélia Gonzalez (1984), who, when dealing with race, class and gender in Brazil, uses the dialectic between consciousness and memory. For the author, making a social analysis based solely on the class struggle, excluding gender and race, is the same as insisting on forgetting these categories and it is the same as denying the subject condition to black women.

It is important to mention that, differently from other perspectives that seek to establish intersections based on identity or other individual and group experiences in a society marked by different types of violence, Gonzalez (2020) articulates race, gender and class based on the social division of labor. A prominent intellectual during an internationalist period of the Brazilian Black Movement and with socialist interlocutors (Domingues, 2024), Gonzalez understands that the classic division of labor, broadly discussed in Marxist tradition, reproduces itself in the Latin-American and Caribbean context as a racial and gendered division of labor. From the centrality of the work category, the education role for the hegemonic reproduction of the productive model is questioned. Thus, the question remains: what is the education for the Brazilian working class constrained by dependency (Bambirra, 2013), by racism (Moura, 1983) and by misogyny (González, 2020; Saffioti, 1978)? Or, as Santos (2024) states, “what is the scientific education for the Brazilian working class today, considering its contradictions and the historicity of its material conformation, in a way of: potentializing the working class resistant forms, organizations and intellectuality; guaranteeing the solid general basic education in attention to the historical and contextual particularities of black people; adjusting itself to the objective contexts of the margins, peripheries and neglected peoples” (p. 12).

The memory erasure that Gonzalez (1984) refers to, also called *memoricide*, demeans non-white people and denies the influence of gender on social inequalities (Costa, 2005), contributing to the reaffirmation of the white man as a universal subject (Souza, 2020). Another author, Nancy Fraser (1997), would categorize these social inequalities as cultural injustice, which must be corrected by recognition policies. A second category of inequalities created by Fraser (1997) is socioeconomic injustice, which must be corrected by redistribution policies. Fraser (1997) also

admits reconciling these two types of policies – recognition and distribution – might be challenging, considering that sometimes they seem to represent opposite interests: individuality and community, respectively. Thus, initiatives that involve these two kinds of policies such as i) the publication of *Lei [Law] 10.639* (2003), which includes in the official curriculum of the Brazilian Education Network the mandatory teaching of the theme "Afro-Brazilian History and Culture"; ii) government actions and the strengthening of public policies for women (Ministério das Mulheres [Ministry of Women], 2023), as a result of the articulations of feminist movements (Costa, 2005), present themselves as a reaction to this memoricide.

Hence, assuming race-gender-class as a thematic and political unit in science teaching can contribute to critical scientific education, adapted to the concrete Brazilian reality. It was from this scenario that we conducted the research described in the following section and proposed an analysis of how the field of science education has conducted the debate on the race-gender-class triad.

In this perspective, we highlight some practical and epistemological consequences arising from the adoption of this unity within the context of science education:

- Recognition of the inseparability of race, gender, education and work categories in the historical processes analysis, safeguarded the particularities and contradictions (unity in diversity), promoting the inclusion/exclusion of scientific and historical themes, debates and contents, thus producing conditions for thematization and problematization of the reality engaged in the anti-racist and anti-sexist struggles, and in the class struggle itself.
- Search for unifying or overcoming exclusive or profoundly particularized approaches, in order to broaden the perception of phenomena and of reality itself, focused on reading society's historical and concrete movement and its effects in the scope of natural sciences production and education.
- Highlight the potential of educational processes, especially, of natural sciences education, in undertaking emancipatory projects with analytic, critical and interruption-transformation capacity.
- All the elements dialectally link themselves to the political dimension of science education which highlights and assumes the historical disputes in terms of contents, methods and axiological aspects of the educational phenomenon.

Methodology

To answer the question posed in the introduction section (how has the debate on the race-gender-class triad been treated in the field of science education in Brazil?), we conducted a text search in all available[1] proceedings of the National Meeting of Research in Science Education (Encontro Nacional de Pesquisa em Educação em Ciências - ENPEC), since 1997, totaling 13 editions. The search terms were: "race" ["*raça*"], "rac", "ethn" ["*etn*"], "negr", "class" ["*classe*"], "gender" ["*gênero*"], "sex"[2]. The papers that presented a connection with at least one of the elements of the aforementioned triad, expressed in their title, abstract and/or keywords[3], were counted in table 1 below.

[1] The proceedings of the II ENPEC, from 1999, were not available on the website https://abrapec.com/enpec-edicoes-anteriores/ and it was not possible to obtain them until the conclusion of this work.

[2] The word search was in Portuguese, because this is the main language at Enpec's proceedings. Also, incomplete words were used to encompass similar terms and those that were not related to the research were excluded.

[3] In most of the available proceedings, it was only possible to use the search tool considering the title of the papers. In these cases, we did not count the search terms that may appear in the abstracts and keywords.

Analysis and Discussion

Table 1 shows that, until the eighth event (2011), there were at most two papers that addressed race or class in their titles. A similar situation occurred with the gender category, but until the seventh event (2009). The number of papers with the race category in the title soared from 1 in 2011 to 5 in 2013. This increase may be related to the spirit of the times, since in the previous year, 2012, *Lei [Law] 12.711* (2012) was enacted, establishing the reservation of places in federal higher education institutions, such as universities, for students from public schools, as well as for black, brown and indigenous people.

Table 1. Number of ENPEC works that mention race, class and/or gender.

ENPEC edition	Race	Class	Gender	Triad
1997	0	1	0	0
1999	-	-	-	-
2001	1	0	1	0
2003	0	0	0	0
2005	2	2	3	1
2007	2	0	3	0
2009	0	1	2	0
2011	1	1	7	0
2013	5	0	13	0
2015	5	1	8	0
2017	6	1	15	0
2019	11	0	30	0
2021	6	0	14	0
2023	15	0	19	0

Subsequently, we read the only paper that presented the three elements (Cabral & Bazzo, 2005) to analyse how this debate was carried out.

The gender category, despite having oscillated in the number of appearances at each event, has maintained its constant presence since 2005. What is noteworthy is that this category has always been more present in ENPEC proceedings than the other two. Although we observed papers that mentioned race and gender, in our textual search, only one cited the three categories – race, gender and class – in its abstract. A possible issue in our research design, that we identified *a posteriori*, was not including search terms as "afr*", "woman*" or "women*" [*mulher**], "girl*" ["*menina**"] and others that, even in a peripheral way, could present an articulated debate involving gender.

This paper (Cabral & Bazzo, 2005), despite considering the race-gender-class triad, does not actually address it. In the introduction section, the authors present statistical data on the gender of researchers in different areas of science and technology (ST) to characterize the background of the investigated group:

> In the field of science and technology education, I conduct a qualitative investigation of socio-historical and epistemological aspects of a group of female professors and

> researchers in engineering and computer science at the Technological Center of the Federal University of Santa Catarina [*Centro Tecnológico da Universidade Federal de Santa Catarina*] (CTC-UFSC). Their accounts, collected as life stories, have revealed a trajectory often marked by inequalities and discrimination in the academic field in which they work, the adoption of strategies to overcome these hostilities, and the work efforts made beyond the efforts of their male colleagues (CABRAL, 2005).
>
> A greater presence of women in this area – I suggest in my work – is strengthened by transformations that involve awareness-raising processes, towards a critical awareness of scientific and technological practice and of gender.
>
> ...
>
> At CTC-UFSC, the average number of female professors and/or researchers is only 15%. Life stories of the investigated group confirm the existence of discrimination and micro-inequalities in the area, requiring them, among other strategies, an "extra effort" in attitude and work, and the delay or renunciation of personal desires. At times distanced/drifted away from research, they shift their interests solely to teaching.[4] (Cabral & Bazzo, 2005, pp. 2-3)

However, there is no mention of ethnic-racial data of researchers, which could contribute to a more qualified discussion about gender and race in the analysed field. As in relation to class, there is no consideration about its implications in work activities in ST, for example. Race and class are mentioned in the abstract referring to the non-neutrality of ST: "The science and technology way under de neutrality myth repelled gender issues, as well as race and social class, for example." (Cabral & Bazzo, 2005, p. 1). Along the paper, the authors write about class to explain the non-neutrality of ST, but there is no in-depth discussion.

> Cerezo and Luján (2001), when discussing the need for a new social contract for science, state that this challenge requires consideration of the cultural, ethical-political, economic, and academic dimensions, as well as the risks with which societies coexist.
>
> According to these authors, these risks would be associated with the "universalization of technology and its negative consequences for the abolition of national, social class, or generational barriers" (Ibid., 2001). In contemporary society, both goods and risks would be distributed – it would be a "society of risk". (Cabral & Bazzo, 2005, p. 3)

As in relation to race, it only appears again in a quote of another author, along with gender, also referring to the non-neutrality of ST. There is a predominance of the gender category and almost no articulation of it with the other two categories, they are not addressed as a triad. Beyond identifying representations, presences or absences of gender, race and class, the main issue we identify is the lack of an articulated analysis of how these dimensions are fundamental to read Brazil's historical problems, along with dependencies, territory and imperialism issues.

In general, although there is acknowledgement of the historical predominance of white men in the field of science to the detriment of black and indigenous people and women in general (Conselho Nacional de Desenvolvimento Científico e Tecnológico [CNPq], 2024), especially in studies on ethnic-racial relations and gender issues, little importance is given to the connection between race, gender and class in science education research. This scenario indicates that the view of white men as universal subjects and the limited space for black and indigenous people, especially women, still exert great influence in the field of science education.

[4] Translated from the original text in Portuguese.

Although socially relevant topics such as race and gender are present in science education research, the lack of articulation between them both and class may indicate a difficulty in recognizing that racism, sexism, and class exploitation are part of the same social structure in which science education is inserted. Finally, resistance to the class debate may be related to the elitist, historically based nature that still permeates science education and academia, neglecting historical research and the deeper problems of our society that require investigative shifts from the micro to the macro and vice versa.

It is worth mentioning a Brazilian author who theorizes about class and race, Clóvis Moura (1983), and states that these two categories are connected dialectically, as components of a productive unity: race and class orient work relations in Brazil (as well as in other countries with a history stained by slavery and segregation based on race). Thus, addressing class and race separately is a way of turning concrete reality invisible. Addressing class-race-gender issues more deeply is important to promote justice in science education, because this way, we can propose remedies, proper to our field, for both socioeconomic and cultural injustices that affect our students and the whole community. As Fraser (1997) states, there is a difficulty in connecting recognition to redistribution, but if we invest in one (often recognition) without the other (often redistribution), injustice will persist.

Conclusion

Affirmative action policies established in legislations such as *Lei 10,639* (2003), *Lei 11,645* (2008) and *Lei 12,711* (2012), as well as government initiatives in gender area, were and are important for the development of an emancipatory scientific education. However, the discussion of the race-gender-class triad, necessary for overcoming social inequalities, is still timid in the field of science education research.

The low number of papers addressing this triad at the main science education research event in Brazil demonstrates a significant gap in academic production and social appreciation of this topic by the community that thinks about science teaching in the country, which struggles with so many inequalities, including both cultural and socioeconomic injustices. Therefore, the results of this research point to the need for studies that address the concrete problems of this field, with the aim of promoting contextualized scientific knowledge, that thinks about scientific practice and questions the history of science, especially in Brazil.

If we want to develop a truly equitable science education, we must first acknowledge its racist, sexist and class-based history. The necessary communication between education, sociology and economic politics poses a challenge to science education researchers, a challenge we have decided to accept and we expect other researchers to do the same. Understanding the constant contradictions in the development of our field of work and study, we can overcome them through other proposals, truly emancipatory, developing policies of recognition and redistribution specific for science education.

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Addressing Girls In Out-Of-School STEM Labs

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Out-of-school labs have been implemented to inspire and inform youth about STEM, to broaden participation, and to counteract the growing lack of STEM professionals. Despite their potential to address persistent inequities in STEM, recent research has shown that pedagogical approaches rather maintain than reduce gendered hierarchies. How girls are addressed in STEM partly depends on the educators and their workshop-related actions, which is affected by their teaching expertise and personal characteristics, such as related values, implicit beliefs or orientations. This study was conducted in cooperation with an out-of-school lab in northern Germany, that faces a decreasing number of girls attending workshops in their spare time. This challenge has led to the following research question: How are girls (not) addressed by the out-of-school STEM lab educators? To answer this question, episodic interviews with N=7 staff members were conducted to gain insights into impressions, experiences and observations during their workshop-related actions. To reconstruct the educators' (possible) gender-related orientations, which result in their workshop-related actions, five interviews were analysed so far using Documentary Method. Relevant topics emerge from the formulating interpretation: organisational design of the workshops, girls' and boys' behaviour and the educators' expertise. Through the reflective interpretation, different reconstructed modi operandi as narrated practices of action could be assigned to three areas: standardisation of a male-connoted STEM culture, gender-differentiated workshop-actions and attribution. By giving an in-depth insight into several orientations about girls in STEM behind the modi operandi, this study outlines the need for out-of-school research being redirected to the role of educators and their gender beliefs.

Keywords: Out-of-School Learning Environments, Science Education, Gender Issues

Theoretical Background

For years, STEM subjects have been accused of gender blindness and structures that continue promoting gender stereotypical education and career choices (Onnen, 2015; Stich, 2024). Traditional gender roles, stereotypes or the lack of role models can be identified as barriers for young women to pursue a career in STEM (European Commission, 2024). The variety of out-of-school STEM labs have the potential to overcome these barriers by making STEM subjects experienceable in an environment without traditional gender role models and the pressure to perform (Baar & Schönknecht, 2018). However, pedagogical approaches, which were originally implemented to provide access to STEM education *for all*, rather maintain than reduce gender-specific hierarchies (Archer et al., 2021).

Within the context of out-of-school STEM learning, researchers have strongly focused on the need to change young people's motivation, identity, or interest regarding STEM through lab interventions (Archer et al., 2021). However, recent findings have shown that research should rather focus on changing the (teaching) offers instead of learners to fulfil its potential for widening participation as well as disrupting gender hierarchies in STEM (Archer et al., 2021; Rodéhn, 2019; Silfver, 2018).

Numerous studies have shown that schoolteachers' performance is partly influenced by their explicit knowledge, pedagogical orientations and subjective values (Elsen, 2020; Hand et al., 2017; Helmke, 2017). This includes implicit knowledge, such as gender-related orientation patterns, which are reflected in their teaching actions, including body language, facial expressions or voice (Elsen, 2020). While there is a broad database on teachers' gender-stereotypical influence in schools (overview in Elsen, 2020), there are hardly results available about educators

in STEM learning contexts outside school (Archer et al., 2021; Rodéhn, 2019; Silfver, 2018). Especially in labs without a link to an educational institution, educators hold a wide range of credentials from formal teaching certificates to no educational practice (Tran, 2008). Research-based findings and developments from the school sector can therefore not simply be transferred here. In addition, it is questionable whether the educators are experienced or qualified in dealing with gender in STEM at all. Hence, it is "necessary to start exploring issues pertaining to educators [and] (…) their understanding of gender" (Rodéhn 2019, p. 163f).

Aim Of The Study

Current research findings show the necessity of adapting the offer on site to promote the participation of young people in STEM and to reduce gender hierarchies (Archer et al., 2021; Rodéhn, 2019; Silfver, 2018). Educators' implicit orientations in out-of-school STEM labs are crucial, because they shape their workshop-related actions. Aiming to investigate educators' implicit orientations about girls in STEM, this exploratory case study was conducted in cooperation with an out-of-school STEM lab in northern Germany without a connection to an educational institution. According to the educators, the number of girls participating in workshops in their spare time is steadily decreasing. This background leads to the following research question:

How are girls (not) addressed by out-of-school STEM lab educators?

Note: Although a gradual opening towards gender diversity in STEM can be observed, research results are still based on a binary gender perspective. These circumstances as well as the fact that the interviewees commonly referred to girls and boys as dichotomous gender characteristics lead to classifying results according to a binary gender definition, which does not represent the perspective of the authors.

Design & Methods

To answer the research question, episodic interviews (Flick, 2000) with full-time educators (N=5) and the management (N=2) in an out-of-school STEM lab were conducted. In contrast to narrative interviews, episodic interviews are characterised by the combination of two methodological approaches: narration and questioning (Flick, 2000, 2011). Accordingly, information about the educators' implicit orientations on girls in STEM are collected through narrative prompts regarding workshop-related situations as well as (feedback) questions based on the narratives that aim for subjective explanations, argumentations or definitions (Flick, 2000, 2011). Beyond obtaining this qualitative data, that method-internal triangulation is suitable for reducing the social desirability bias, which has an influence on responses referring to sensitive topic of "gender" (Wolter, 2022). The educators' professional qualifications differ widely (e.g., apprenticeship in carpentry, a degree in mechanical engineering with a specialisation in aerospace engineering or a doctorate in geology). Among the educators and the management, four people identified themselves as female, two as male and one as human. At the time of data collection, the interviewees were between 27 and 74 years old.

The episodic interviews were analysed by using Documentary Method according to Nohl (2010, 2017). This reconstructive analysing method is particularly suitable for gaining a profound insight into implicit, possibly gender related orientations, as the analysis focuses not only on the narrated practice of action (modi operandi), but also on how it was said as well as its context (Nohl, 2017; Rabe et al., 2023). For this purpose, the Documentary Method involves three core analytical steps: In the formulating interpretation, sections relevant to the research question are identified, thereby capturing the explicit content level of what was said in terms of topics. In the subsequent reflecting interpretation, underlying orientations about girls in STEM are elaborated behind the

narrated practice of action (Nohl, 2017). The third core element, the comparative sequence analysis, enables the contrast of relevant interview sections within and across cases to identify internal linguistic and/or (workshop-related) action logics or breaks. Regularly participating in research- and interpretation-colloquia serve to ensure the scientific quality of one's own interpretation and to continuously reflect on one's own location-boundness (Rabe et al., 2023).

Insight Into Preliminary Results

The analysis of five interviews, including the core steps described above, has been fully completed. The following relevant topics emerged from the formulating interpretation: organizational design of the workshops, the girls', boys' and educators' behaviour in the workshops as well as the educators' expertise.

During the reflective interpretation, a range of internal action logics could be reconstructed, which can be divided into three areas: standardization of a male-connoted STEM culture, gender-differentiated actions in the STEM workshops, and attribution. The educators' narrated action practices (modi operandi) show that they implicitly associate math, physics, computer science, and technology with masculinity. This is evident, for example, in the choice of workshop topics (programming car racing games) or the standardization of boys' (dominant) and girls' (cautious) behaviour. This implicit standardization results in specific gender-differentiated workshop actions, such as addressing girls by topics based on gender-specific stereotypes (natural cosmetics or jewellery soldering), encouraging girls ("you can do it"), working in gender-homogeneous groups, or concealing male-connoted STEM disciplines by avoiding "provocative" words (e.g., "graphs"). It was also mentioned that girls in the workshops need to be protected from dominant boys who devalued their work. Finally, all educators draw conclusions referring to the youth's interest based on the behaviour the educators observe: for example, the dominance of boys is attributed to a high level of interest, while the girls' restraint is implicitly assumed to indicate little or no interest.

The reconstructed logic behind the educators' modi operandi is based on their collectively shared belief that "STEM is male". This leads them to implicitly characterize girls as a target group that deviates from the norm in STEM, meaning that alternative approaches are needed to address them in STEM. These alternative approaches result in an implicit need for girls' own topics, own language, and own treatment in STEM workshops. Thus, in terms of their narrated practice actions, educators implicitly assume that addressing girls in STEM requires additional effort.

Discussion

The preliminary results clearly show that a variety of gender-specific orientations can be reconstructed, which make educators implicitly reproduce gender hierarchies and prevent girls from feeling a sense of belonging in STEM (Archer et al., 2021; Çolakoğlu, 2024). It is questionable why these orientations are so powerful, even though the decreasing participation of girls is regularly discussed within the team. Further studies are needed to investigate possible reasons. Educators implicitly believe that they are addressing girls by means of the gender-specific actions outlined above. However, their (explicit) narratives made clear that girls do not feel addressed, but rather that their feeling of "not belonging" is implicitly reinforced by the additional effort that was made (Çolakoğlu, 2024). With reference to Çolakoğlu (2024), working in gender-homogeneous groups initially seems to be a sensitive short-term solution to strengthen girls' sense of belonging against the backdrop of a male-dominated environment. In the long term, however, these groups are very exclusive in nature, reproducing gender and subject-related stereotypes and confirming implicit assumptions about the need to make extra effort for

addressing girls. Due to the lack of a sense of belonging, girls' participation in voluntary activities at the out-of-school STEM lab would probably remain low (Çolakoğlu, 2024).

Implications

As initial results from the project already indicated, there is not only an urgent need for action to minimise the impact of educators' implicit, gender-stereotypical orientations, but also to shift research's focus on the role of educators and their competencies regarding gender in STEM. Referring to the enormous diversity of out-of-school STEM settings in Germany, considerations about suitable interventions cannot (and should not) result in an overarching "recipe" for qualifying all out-of-school educators working in STEM labs. Even more, this study indicates providing support for educators to regularly reflect on their implicit, gender-stereotypical orientations. Additionally, it is conceivable to formulate corresponding competencies as recruitment requirements or to anchor the topic of gender in STEM as a fixed component of continuous professionalization opportunities for educators in out-of-school STEM labs.

Outlook

The Documentary Method will be further conducted to first analyse the last two interviews and secondly further contrast them with the (already) reconstructed modi operandi as well as those underlying orientation patterns. Additionally, episodic interviews with other STEM educators are planned to further contrast between the reconstructed gender-specific orientations, which result in the educators' workshop-related actions. A criteria-based selection of suitable STEM labs is already made.

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The Influence Of School Experiences In The Construction Of A Scientific Identity – A Case Study With Brazilian Transgender Persons

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This qualitative case study investigates the influence of school and science classroom experiences on the construction of a scientific identity among transgender individuals in Brazil. Drawing on Foucauldian theories of disciplinary power and on the concept of Science Capital, the research analysed the narratives of eight transgender participants collected via online questionnaires. The findings reveal a dichotomous influence: profoundly negative experiences — characterized by systemic bullying, discrimination, spatial precarity, and institutional neglect — actively dismantle Science Capital and divert individuals from scientific paths. Conversely, affirmative experiences, particularly through supportive and gender-sensitive science teachers who provide recognition and mentorship, can foster resilience, build Science Capital, and catalyse the pursuit of scientific careers, often as an act of social resistance. The study concludes that the school environment functions as a critical filter, either reinforcing exclusion or enabling inclusion. It underscores the pivotal role of educators and institutional policies in shaping trajectories and calls for urgent structural reforms—including teacher training, curriculum revision, anti-bullying programs, and affirmative actions in higher education—to transform educational spaces into equitable foundations for scientific identity development among transgender students.

Keywords: Equity in Education; Gender Equity; Science Identities

Introduction

Gender identity and sexuality play a crucial role in shaping social interactions and career choices, deeply tied to one's sense of belonging. In Western societies, the male/female binary is a foundational element of capitalist and colonial structures, dictating social roles and labor opportunities—particularly in peripheral regions such as Latin America, where heteronormative authority continues to subordinate women and gender-diverse minorities.

This structural inequality is starkly evident in Brazil, which records the world's highest rates of murders and suicides among transgender and non-binary people. Widespread transphobia permeates all spheres of life, including education and future professional prospects. Although transgender and non-binary individuals represent 2% of the population, they account for only 0.3% of university students, with most abandoning school between ages 14 and 18 (Observatory of LGBTI+ Deaths and Violence in Brazil, 2025).

Prejudice is especially severe for trans women, reflecting socio-historical processes that silence femininity (Junqueira, 2016). The formation of gender and sexual identities is intrinsically linked to power relations (Seffner, 2011), and transgender people face systematic human rights violations worldwide, intensified by their visibility and the inability to conceal their gender identity (Rodrigues, 2011).

Foucault (1988) studied power relations and how they manifest themselves in social institutions. He argues that modern society is structured around complex networks of power that exert control over the bodies and identities of individuals, exercised through norms, discourses and practices that define what is considered normal. In the context of transsexuality, Foucault's insight can be applied to understand how educational institutions perpetuate gender norms that marginalize

those who do not conform to binary gender expectations. Foucault suggests that power is not only repressive, but also productive, in that it creates categories of identity and regulates behaviours through mechanisms of discipline and surveillance.

For Foucault, school is one of the main institutions that contribute to the formation of subjectivities, using a series of disciplinary techniques to shape behaviours and identities. These techniques include constant surveillance, ongoing assessment and normalization, which together work to reinforce prevailing gender norms. Transgender individuals who challenge these norms often face discrimination and exclusion, which can have a significant impact on their educational experience and psychological well-being.

Furthermore, Foucault highlights the importance of discourse in constructing identities and maintaining power relations. Medical discourse, for example, has historically pathologized transsexuality, classifying it as a disorder or abnormality. At school, this pathologization can manifest itself through discriminatory practices and the lack of inclusive policies that recognize and respect the diversity of gender identities.

For transgender people, the need for authenticity in expressing their identity often collides with social and institutional expectations, generating conflicts that harm concentration, active participation and knowledge acquisition. Thus, addressing the school experiences of transgender people is crucial for the creation of a more democratic and inclusive environment at schools and to promote equity and social justice.

Besides, few studies have addressed the formation of scientific identity of transgender students. Recently, Datta (2024) reported the results of an investigation about how transgender people negotiate identity and community questions in Indian science institutions, showing that the lack of social capital strongly determines their professional trajectories. Archer and coworkers (2019) had already delt with the relations between gender and the development of scientific identity when analysing groups of British students at high school, showing that Science teachers tend to endorse their male students' discourses.

Thus, investigating school experiences of transgender people is crucial for the development of a more inclusive environment, where they can build confidence on their abilities to pursue a scientific career. Thus, the objective of this paper is to describe our research on the experiences of a group of transgender people in Science classes and how they influenced in their professional choices. Our research question can be pointed out as: how Science class experiences influence in the adhesion of Brazilian transgender people to a scientific identity/career?

Theoretical background

Historical analysis reveals that transgender phenomena and gender diversity are not modern constructs but have ancient roots. Furthermore, many non-Western societies have historically treated gender variance as a sacred or mystical experience, distinct from the rigid Western binary (Correa, 2020). In Brazil, evidence of trans existence dates to the 16th century, with figures who resisted imposed gender norms despite persecution and derogatory descriptions in colonial records (Mott, 2005). The 20th century witnessed both severe repression — such as the targeting of trans people during the Military Dictatorship under accusations of subversion — and gradual medical and legal recognition.

The pathologization of transgender identities has been progressively challenged; homosexuality was declassified as a mental disorder by the APA in 1973 (and fully removed from the DSM-III in 1980) and by the WHO in 1990, while transgender identity was initially categorized as Gender Identity Disorder in the DSM (1980), later renamed Gender Dysphoria (2013), and more recently

defined as gender incongruence in the ICD-11 (2018), moving away from a pathological framework (Coacci, 2020). This historical trajectory underscores the long-standing presence of trans identities and the shifting socio-medical discourses surrounding them.

Human sexuality transcends mere biological differences, enabling research to incorporate the social dimension of gender (Melo & Sobreira, 2018). A fundamental distinction lies between sex (biological attributes) and gender (a sociohistorical construct), a conceptual advance that challenges the historical conflation of the two, which naturalized behaviours and social roles based solely on biology (Jesus, 2012). Gender is thus understood as a normative construction that assigns characteristics as masculine or feminine (Oka & Laurenti, 2018). Central to this framework is gender identity—an individual's subjective sense of self, which may be cisgender (aligned with sex assigned at birth), transgender (non-aligned), or non-binary (Jesus, 2012). This must be distinguished from sexual orientation, which pertains to affective-sexual attraction toward certain genders (Siqueira & Klidzio, 2021), illustrating the broad spectrum of human relations (Jesus, 2012).

Drawing on Michel Foucault's seminal work, schools can be understood as quintessential disciplinary institutions that actively produce and regulate normative gender identities. Through mechanisms of constant surveillance, evaluation, and the normalization of behaviours, educational environments reinforce a rigid gender binarism (Foucault, 1987). This disciplinary power operates not merely through repression but productively, shaping subjects by defining what constitutes a "normal" boy or girl, thereby marginalizing those who deviate from these cisheteronormative expectations. The historical pathologization of transsexuality within medical discourse, as analysed by Foucault (1988), finds its parallel in school practices that, often through omission or discriminatory behaviour, treat transgender identities as anomalies to be corrected or silenced. This framework illuminates how institutional structures systematically enforce gender norms, rendering transgender students vulnerable to exclusion and psychological harm as they challenge the established binary order.

However, this Foucauldian analysis also reveals the potential for resistance and transformation within the educational field. If power is diffuse and productive, it also creates spaces for counter-discourses and practices. The very institution that disciplines can be reimagined as a site of emancipation (Frigotto, 2001). Moving beyond a pathologizing view requires recognizing transgender existence as a legitimate form of subjective experience and social being, as emphasized by theorists like Arán, Murta, and Lionço (2009) and Butler (2009). From this perspective, education transforms into a tool for challenging the norms it has historically upheld. This entails actively deconstructing the heteronormative matrix (Louro, 2013) and cisnormative pedagogies (Junqueira, 2016) embedded in curricula and daily interactions.

Therefore, the potential for schools to become inclusive spaces hinges on a deliberate shift from disciplinary normalization to the affirmation of diversity. This requires implementing concrete policies that protect and respect gender identity, coupled with continuous teacher training to foster sensitive and informed approaches. By critically engaging with and disrupting the power relations that sustain gender binarism, education can fulfil its emancipatory promise. It can become a space where diverse gender identities are not only recognized but valued, allowing all students, especially those from marginalized groups, to fully access knowledge and build their futures without having to renounce their authentic selves.

The construction of a scientific identity is deeply intertwined with issues of access, representation, and social validation. Drawing on the work of Archer and colleagues, the concept of "Science Capital" is crucial here; it posits that the aspiration to pursue science is not merely an individual choice but is significantly shaped by one's access to a composite of economic, social, and cultural

resources specifically related to science. This framework helps explain how systemic inequalities — such as those based on gender, class, and race — can limit the development of a scientific identity from an early age, as historically seen in the exclusion of women, particularly poor and Black women, from exact and natural sciences. For transgender individuals, these barriers are compounded by a profound lack of representation and institutional recognition, which directly impacts their sense of belonging and possibility within scientific fields.

This marginalization is mirrored and reinforced by a prominent academic void. As highlighted by Moura and Zibetti (2023), there is a severe scarcity of research focusing on the schooling of transgender people in Brazil. Their systematic review, which filtered thousands of records down to only 28 relevant studies, reveals a field that is incipient, fragmented, and geographically concentrated in the South and Southeast regions. This research gap is not neutral; it reflects and perpetuates the structural invisibility of trans experiences in educational policy and discourse. The lack of interdisciplinary studies, especially from fields like Psychology that could illuminate subjective and psychosocial dimensions, means the specific challenges transgender students face in forming a scientific identity remain largely unexamined and unaddressed, thereby allowing cycles of exclusion in science education to persist unchallenged.

Methodology

This study is characterized as an applied, qualitative research, configured as an exploratory case study (Yin, 2001). The qualitative approach was chosen as it aims to investigate how individuals perceive and attribute meaning to their experiences, ideas, and events (Câmara, 2013), allowing for an in-depth understanding of the participants lived educational trajectories. The case study design was appropriate for obtaining insights from the detailed experiences of a specific group within their real-life context (Creswell, 2010).

The research involved eight transgender individuals (including both trans men and trans women), aged between 19 and 36, from different Brazilian states (Rio de Janeiro, São Paulo, and Pernambuco). Participants were recruited virtually through a non-probabilistic sampling technique, where invitations were directed to individuals who self-identified as transgender in their Instagram biographies. To ensure privacy, comfort, and an environment conducive to authentic sharing, all data were collected anonymously, with no request for identifying information such as names.

Data collection was conducted via an online questionnaire on the Google Forms platform, enabling access to participants from various regions. The instrument contained both open and closed questions, structured into three thematic blocks: (i) sociodemographic data, (ii) school and academic experiences, and (iii) professional experiences in teaching (where applicable). The questionnaire covered topics such as experiences of respect or discrimination in school, relationships with science teachers, access to higher education, and perceptions of the work environment.

For data analysis, documentary analysis and content analysis were employed, following the principles proposed by Bardin (2016). The process followed three fundamental stages: pre-analysis, material exploration, and treatment of results. From the responses, four core analytical categories were established based on the recurrence of themes and the research objectives: 1) School Experiences (encompassing bullying, discrimination, and sense of belonging), 2) Relationship with Science Teachers, 3) Experiences in Higher Education, and 4) Professional Trajectory and Teaching. These categories guided the interpretive analysis, allowing the participants' narratives to be critically examined considering the theoretical framework on education, diversity, and the inclusion of transgender people.

Results And Discussion

Guided by the dual theoretical lenses of disciplinary power (Foucault) and Science Capital (Archer et al.), this section analyses participants' narratives to address the central research question: how do Science class experiences influence the adhesion of Brazilian transgender people to a scientific identity or career? The analysis examines these accounts as lived experiences where the theoretical mechanisms of normalization and exclusion materialize concretely, while also highlighting moments of affirmation and resistance that directly shaped their relationship with science. This approach allows us to understand how specific interactions in the science classroom impacted their sense of belonging, access to scientific resources, and ultimately, their trajectory toward or away from a scientific career.

The school environment emerged from the narratives as a primary site of disciplinary power, where violence and exclusion enforce gender binarism. All interviewees reported severe bullying, from verbal harassment to sexual abuse. Interviewee H recounted: "Physical education classes were terrifying... they made my life hell, assaulted me physically, mentally, sexually, turning me into the class joke." This multiform violence targets non-normative bodies, seeking to render them docile (Foucault, 1987), and initiates a cycle of psychological suffering that corrodes self-worth and belonging (Aran et al., 2008). Exclusion was perpetuated not only by peers but through institutional neglect. Interviewee D noted a dissonance: "The teachers listened to my proposals... but often my gender identity was not respected," reflecting a form of symbolic violence born from a lack of understanding and inclusive policies (Bronzo, 2010).

The consequences were directly academic and aspirational. The relentless bullying described by Interviewee H led to plummeting grades and the abandonment of her medical career aspirations after a cruel incident in Grade 9: "The damage was already done, they broke me." This trauma hit her nascent Science Capital (Archer et al., 2015), depleting the resources necessary to sustain scientific identity formation. This illustrates how exclusionary environments actively dismantle, rather than build, the professional trajectories of transgender students.

The Foucauldian analysis is further concretized in the issue of spatial control, such as the acute anxiety around bathroom use mentioned by Interviewee E. This fear is a manifestation of spatial discipline and surveillance (Foucault, 1987). Bathrooms, as rigidly gendered binary spaces, become sites of normalization and potential confrontation, placing transgender students in a state of spatial precarity. This daily practice reinforces binary norms, invalidates their identity, and consumes cognitive energy that could be directed toward learning, creating a tangible barrier to educational engagement and academic belonging.

While the school environment emerged as a pervasive system of disciplinary power that actively eroded belonging and dismantled Science Capital, the participants' narratives revealed that specific actors within this system could function as decisive counterweights. This dynamic between structural exclusion and potential affirmation brings into sharp focus the pivotal role of educators. The following analysis examines the agency of science teachers, exploring how their pedagogical stance — ranging from conscious inclusion to passive neglect — directly mediated the impact of the hostile school climate. Their actions crucially determined whether initial student interest in science was validated and nurtured into tangible Science Capital or whether it was extinguished by the broader culture of exclusion.

Within the often-hostile school environment, Science teachers emerged as pivotal figures capable of acting as counterweights to disciplinary exclusion, directly influencing the participants' relationship with scientific knowledge. Positive reports highlighted teachers who respected

gender identity and actively engaged students' interests. Interviewee H recalled, "I always liked sciences, especially natural sciences. My teachers were very open and treated me equally, which made me consider the area as a career option when I was younger." This respectful and equitable treatment, as Oka and Laurenti (2018) argue, is fundamental for creating an inclusive pedagogical practice that can foster sustained interest in science among marginalized groups. Similarly, Interviewee D received significant support from her teacher, who encouraged her participation in national science and biology olympiads. This active mentorship provided her with specific forms of Science Capital (Archer et al., 2015) — such as access to special knowledge (Olympiad preparation), institutional recognition, and a network of support — that validated her scientific competence and belonging.

However, these affirming experiences contrasted with a broader institutional failure. Four interviewees stated they received no encouragement from teachers or schools to pursue science. This widespread lack of formal support reveals a systemic gap where personal interest was not translated into concrete aspirational identity due to absent mentorship, career information, or validation of scientific potential.

The analysis of these contrasting experiences underscores the teacher's dual role as both a potential agent of inclusion and an unwitting accomplice to systemic neglect. The positive cases demonstrate that when educators consciously adopt a gender-sensitive approach, they do more than transmit content; they perform an act of identity affirmation. By treating a transgender student with equality and actively promoting their participation, these teachers directly combat the pathologizing discourse and social exclusion their students face elsewhere. They become facilitators of Science Capital accumulation, building the social and cultural resources necessary for scientific identity formation. Conversely, the more common absence of active encouragement, even amidst otherwise respectful treatment, reflects a pedagogical shortcoming.

The influence of science teachers proved to be a critical variable, either facilitating a connection to scientific knowledge or reinforcing a sense of alienation from it. However, the translation of this school-based Science Capital into sustained scientific trajectories hinges on the subsequent gateway of higher education. The journey into and through university represents a contested stage where earlier experiences of support or exclusion are recontextualized within new structures of power and recognition. It is marked by profound structural inequalities. As evidenced by the interviews, access is not guaranteed, with financial and social barriers acting as significant gatekeepers. Interviewee B’s situation, who "could not attend college due to a lack of financial resources and opportunities," exemplifies the social vulnerability described by Filgueiras (2004), where systematic marginalization deprives groups of essential resources like education. The empirical reality of these barriers underscores the theoretical point that exclusion is not merely incidental but a structured outcome, preventing many from even entering university space.

Once within academia, the experiences diverge sharply, revealing the university as a deeply contradictory space. For some, it becomes a transformative environment for self-knowledge and affirmation, what resonates with Bento's (2014) conception of the university as a conducive context for the dynamic and non-linear process of gender reinvention, offering the freedom to reconnect with one’s identity. Conversely, others confront persistent invisibility and new challenges. Interviewee C, despite some growth, felt "constantly invisible," while Interviewee H’s earlier engineering studies were marked by intense depression and isolation, leading to severe mental health struggles. This contrast illustrates the dual potential of the university: it can be a site of emancipation for some while perpetuating normative exclusion for others.

This duality exposes the university as an arena where both liberation and normative control are negotiated. The positive accounts of Interviewees E and F, who found in university an opportunity

to "liberate themselves in relation to their own body" and experience a "process of self-construction," align with Bento's (2014) view of academia as a space for personal emancipation from previous social restrictions. However, the "invisibility" reported by Interviewee C and the pathologizing marginalization discussed by Marreiros e Silva (2015) reveal how institutional spaces often maintain a binary gender logic that silences trans presences.

Ultimately, the empirical data compels a critical synthesis: the university is a microcosm of broader social tensions regarding gender. True transformation, as theorized by Bento (2014) and Perelson (2011), requires actively dismantling the normative frameworks that render trans identities secondary.

The ambivalent nature of higher education — as both a site of liberation and of continued normative exclusion — frames the ultimate stage in the pathway toward a scientific identity: the professional career. The analysis of the experiences described by the interviewees reveals how a scientific identity, when achieved, is often enacted as a form of social resistance. It directly answers how adverse school experiences can ultimately lead not only to withdrawal from science but also to a resilient, politically charged commitment to transforming scientific and educational spaces for future generations.

Six of the interviewees opted for a degree in Education. The choice to enter the teaching profession emerges from the interviews as a deliberate act of social resistance and transformation. Interviewee D's trajectory is paradigmatic; she explicitly pursued a teaching career "with the aim of deconstructing the stigma that transgender people are not socially or intellectually capable." This motivation is deeply rooted in her own positive schooling experience, where supportive science teachers encouraged her participation in competitions and emphasized pursuing higher education. Her decision to become a Biology teacher, therefore, transcends mere career choice, embodying what Frigotto (2006) conceptualizes as education mobilized for the construction of a more just society. By seeking to "destigmatize gender prejudice" through pedagogy, she positions teaching not as the neutral transmission of knowledge, but as a critical practice that challenges oppressive norms and aims to transform social reality. This aligns with the resistance movement described by Frigotto and Ciavatta (2012), where education becomes a tool to contest the very structures of discrimination.

The reported current work experiences of the trans educators reveal a professional environment that is both affirming and demanding of constant resilience. Empirically, the accounts are "profoundly positive and inspiring," with Interviewee C describing his teaching experience as "incredible" and feeling like a "potency inside the classroom." Similarly, Interviewee F shares being "incredibly respected" during teaching internships, particularly regarding discussions on gender and transness. These positive experiences reflect Perelson's (2011) notion of recognition, where professional respect becomes foundational for affirmed identities and suggests that educational spaces can indeed become sites of empowerment. However, this affirmation coexists with the need for persistent self-assertion. As Interviewee C notes, the requirement to constantly impose himself to avoid delegitimization highlights the ongoing structural prejudice that necessitates a resilient and proactive stance. Thus, while their teaching practice is transformative for themselves and potentially for their students, it is continuously enacted within a context that still requires them to navigate and resist marginalizing forces.

In synthesis, the professional trajectories of these interviewees exemplify teaching as a transformative practice in a dual sense. First, it serves as a personal and political vehicle for resisting stigma and reclaiming social legitimacy, as theorized by Frigotto. Second, their active presence in classrooms performs a transformative social function, potentially altering the educational environment for future generations. The empirical data demonstrates that their

pedagogy is intrinsically linked to a project of social change. Their generally positive workplace experiences indicate progress, yet the undercurrent of needed resilience confirms that their transformative work occurs not in a void of acceptance, but through continuous engagement with and resistance to persistent normative structures.

Conclusions

This study concludes that experiences in science classes and school environments are decisive in shaping the scientific identity and career trajectories of transgender individuals. The empirical data reveals a sharp dichotomy: profoundly negative experiences, marked by discrimination, abuse, and exclusion, can cause deep trauma and divert individuals from scientific paths, as exemplified by Interviewee H who abandoned a medical career after feeling she "would never be accepted." Conversely, positive and inclusive experiences, centered on respectful and encouraging relationships with teachers, can foster a strong scientific identity and resilience. The testimony of Interviewee D, who received "consistent support from her teachers" leading her to become a Biology teacher, underscores how affirmative pedagogical relationships can empower trans students to pursue and thrive in scientific careers.

In direct answer to the research question — how Science class experiences influence the adhesion of Brazilian transgender people to a scientific identity/career — the findings demonstrate that these experiences function as a critical filter. They can either act as a mechanism of exclusion, reinforcing societal stigma and severing the connection between trans students and scientific fields, or as a catalyst for inclusion, providing the recognition and support necessary to build a scientific identity and a trajectory of resistance through education.

Based on these conclusions, urgent and multidimensional actions are recommended. At the policy level, this includes revising educational policies to incorporate specific guidelines for gender equity and the protection of transgender students. Institutionally, mandatory pre- and in-service teacher training on gender diversity and inclusive pedagogies is essential. Within Science education, a reformulation of curricula is needed to critically address concepts of sex and gender, thereby incorporating human diversity and deconstructing cisnormative biases. Schools must implement robust anti-bullying programs and establish integrated psychological and social support networks. Furthermore, to address barriers in higher education, affirmative actions for transgender access and permanence must be promoted. This study acknowledges its primary limitation as a qualitative case study with a small sample. Future research should expand on these insights through larger-scale, quantitative or mixed-method studies with more diverse demographic samples, as well as longitudinal designs that follow the educational and professional trajectories of trans individuals over time.

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Science Capital Of Brazilian Students From The Periphery Of Rio De Janeiro: Correlations Between Gender, Ethnicity And Parents' Educational Level

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Science Capital, introduced by Archer and coworkers, is based on Bourdieu's concept of capital and how students' cultural, social and economic capitals influence the formation of a scientific identity and future career engagement. Higher Science Capital is linked to families with strong ties to science, with gender and ethnicity also playing a role. A key outcome of their research was a questionnaire assessing three dimensions—scientific cultural capital, science-related behaviours, and scientific social capital—generating a score from 0 to 105, classified as low, medium, or high. Since 2018, our group has been studying the Science Capital of public school students, who represent over 80% of Brazilian students mainly from lower-income backgrounds, with the aim of investigating the factors that promote inequalities in engagement with science. In this context, public schools both reflect social inequalities and provide opportunities for equity and social justice. Our research involved 936 high school students (ages 14-20) from six public schools in the metropolitan region of Rio de Janeiro, using a Portuguese-adapted Science Capital questionnaire. Results indicated a predominance of medium Science Capital levels, with the mother's educational level being the primary influencing factor. More male students were in the medium level, while gender non-normative students had a higher proportion in the high level. These findings emphasize the role of gender in Science identity formation and the need for policies promoting gender equity in education to ensure more inclusive access to scientific careers in Brazilian public schools.

Keywords: Educational equity, Equity in Science, Science Identities

Introduction

Science Capital is a concept developed by Archer and coworkers (2015) based on the Bourdieusian concept of capital and taking into consideration the school educational field. The concept was developed from their participation in the ASPIRES project (King's College, 2013), aimed to reflect the reduction in the interest of following scientific careers by young people.

The authors suggest that the legitimization of resources related to science is an important form of contemporary capital as they play a significant role in producing social relations of advantages and disadvantages, not only due to their high symbolic and exchange value in contemporary society, but also because science is conceived, in various international contexts, as a national priority within government policies (Archer et al, 2015). Thus, as we live in a society that continuously uses science and values it as important, the authors aimed to add new contributions to Bourdieu's theory of capital, specifically regarding scientific matters, which could contribute to a more democratic society.

After the initial study, other researchers have used this approach to evaluate the Science Capital in different countries, such as Finland (Kaakinen et al., 2023) and Singapore (Teo et al., 2018). In Brazil, our group has been developing research on the Science Capital of students since 2018, with a major interest in investigating the factors that influence the choice of a scientific career by female students from low income, peripheral neighbourhoods (Silva, Teixeira & Silva, 2023). Our investigation with ten students from five public schools from the Metropolitan region of Rio de Janeiro has shown that participating in science projects was the only way they could interact

with science professionals and science-related professions. We could also observe that those students had their mothers as professional inspirations and, so, they have a crucial role in their future professional choices. The girls that foresaw Science as a professional possibility pointed out that social media, TV shows and their teachers played a pivotal role in this choice. As a result of this research, we developed an e-book with orientations for teachers who wish to promote the development of the Science Capital of their students.

Our research group has recently published a paper (Mileo Jr & Silva, 2025) describing the results of research on the scientific aspirations of two groups of Brazilian students from different educational systems, using data collected with Archer's Science Capital questionnaire. The first group, composed of students from a Federal public school, displayed higher levels of cultural and social capitals than those of the other, composed by students of public schools ruled by the State of Rio de Janeiro local government. These results are reflected in a greater adherence of the former group to a scientific identity. Scientific aspirations are strongly influenced by social inequities within the groups and thus educational policies related to Science education are necessary to promote equity and social justice among these schools.

The research described in this paper deals with an investigation of students from six schools located in the metropolitan region of Rio de Janeiro, the second largest city of Brazil, aiming to answer the following questions: how the students at the analysed public schools are distributed in the three levels of Science Capital? In which extension can the sociodemographic data of these students explain this distribution? Are there relationships between our data and those found by Archer and coworkers (Archer et al., 2015)?

Theoretical Background

According to Archer (Archer et al, 2015), Science Capital is not a different kind of capital, but a way of grouping aspects of the social, cultural and economic capitals that are more related to creation and value exchanges that leads to a higher participation or adhesion to a scientific identity or career. The concept is related to the theory of social reproduction (Bourdieu, 1983) and, consequently, the values attributed to what is established as scientific capital are a function of the social context (field), and the strategies for obtaining this capital are directly linked to individuals' nonconscious perception of their position within this context (*habitus*). Thus, Archer synthesizes the relationship between the values and logics that shape students' engagement with science. In her view, Science Capital is a function of all the ways students relate to scientific knowledge, which can be understood through the following main dimensions: scientific literacy; attitudes and values related to science; scientific behaviours outside of school; and contact with people who work in science (Godec et al., 2017).

Considering these dimensions, the first results of Archer group's research showed that a higher Science Capital was associated with students who belong to a family with higher social and cultural capital associated with science. Other factors that influence the levels of Science Capital are gender and ethnicity, with higher levels being more likely to be found among white male students from high cultural capital families, in which at least one member has a Science related career. On the other hand, female students and black students suffer numerous experiences throughout their lives that lead them to believe that Science is not for them at all (see also Archer et al., 2019).

From measuring Science Capital, it becomes possible to develop diagnostic processes regarding students' relationships with elements of the different dimensions and to propose guidelines to increase their engagement with science. One of the key achievements of Archer research was the development of a questionnaire that can be used to quantitatively measure Science Capital

(Archer et al, 2015). The questions are divided in three dimensions (scientific forms of cultural capital, behaviours and practices related to science, scientific forms of social capital) from which 14 specific items were used to calculate the Science Capital, that can vary from 0 to 105. These values can be ranked in three different levels: low (0-34.5), medium (35-69.5) and high (above 70).

Methodology

We are particularly interested in the levels of Science Capital of young people studying at public schools, since they are frequented by more than 80% of the Brazilian students, especially those from the lowest economic income fraction of the society. This makes the public schools a scenario for the reproduction of the social inequities of Brazilian society, as well as a field to provide experiences that can promote equity and social justice. Understanding the distribution of the students in the three Science Capital levels and its relationship with their sociodemographic data may open opportunities to develop activities which can potentially enhance their social and cultural capital related to science.

The research was then conducted with 936 high school students from six public schools from the metropolitan region of Rio de Janeiro, Brazil. All of these schools are in peripheric, low-income districts and with limited financial support from the local government, which restricts the pedagogical opportunities available to teachers to overcome educational inequities. There is an important index of school evasion during the first year of High School, when boys are required to find an occupation to improve their family income. On the other hand, girls can leave school or reduce their time of dedication to their studies to take care of domestic affairs or due to an early pregnancy.

The students, ranging from 14 to 20 years old, answered a version of the Science Capital questionnaire (Archer et al. 2015) translated to Portuguese, with minor adaptations necessary to adjust the questions to the cultural and institutional realities of the schools. The answers were collected and treated using Excel. One-factor ANOVA tests were performed at $p < 0.01$. The answers were submitted to Cronbach's alpha test, which verified the internal consistency of the data collected (Table 1). After that, the Science Capital was calculated following Archer's methodology, and the students were grouped in the three levels (low, medium and high Science Capital) as described before. Then, correlations between these levels and the sociodemographic data collected in the same survey were drawn to find how these factors are associated with the construction of the students' Science Capital.

Table 1. Cronbach's alpha for the subdimensions of the Science Capital questionnaire.

Component	Cronbach's alpha*
Future science job affinity (aspirations)	0.66
Valuing science and scientists	0.69
Family attitudes (including attitudes to science)	0.74
Utility of science qualifications	0.76
'Informal' science activities	0.63
Science media engagement	0.75
Valuing museums/ museum experiences	0.79
Science teachers and lessons	0.77
Self-efficacy in science	0.66

* Cronbach's alpha values above 0.6 were considered satisfactory (Wartha & Santana, 2020).

Results And Discussion

Sociodemographic (gender, ethnicity and parents schooling) data of the analysed population are resumed in Table 2. It was composed equitably by male and female students. Most of them declared to be Black, which is consistent with Brazilian demographic (Brasil, 2025) data and with the fact that most of the lowest income families are composed of this ethnic group as a consequence of the strong marks of African slavery and the way its abolition was unfairly conducted in Brazil.

Table 2. Sociodemographic data of the students.

	Gender			Ethnicity		
	Male	Female	Other*	White	Black	Other*
n (%)	447 (47.8)	443 (47.3)	46 (4.9)	220 (23.5)	630 (67.3)	86 (9.2)

* Other response/Preferred to not answer

The percentual distribution of the students in the three levels of Science Capital is depicted in Table 3, together with data related to their family's cultural capital. Most of them are in the medium stratum and less than 1% was ranked with high Science Capital, while Archer's initial study pointed to a percentage of 5% at this level among British students.

Table 3. Science Capital and Parents' Educational Level (n = 936).

	Low (%)	Medium (%)	High (%)
Science Capital	45.7	53.5	0.7
Mother left the school before 16 y.o.	23.8	27.7	0
Mother frequented a university	7.2	13	28.6
Father left the school before 16 y.o.	25.2	28.3	28.6
Father frequented a university	6.3	12.4	14.3

The data highlights that the mother's educational level is a more significant predictor for achieving a high Science Capital score than the father's educational level, which exhibits a weaker influence. Feijó, França, and Pinho Neto (2022) studied the influence of mothers on the academic performance of Brazilian high school students. Using a national government database on student scores in the ENEM (the national university entrance exam), the authors found that a mother's level of education has a greater impact on her children's academic performance than the father's level of education — an effect that is stronger among daughters, particularly when the mother holds a university degree. This influence was independent of the traditional channels of educational transmission — the identifiable means through which higher parental education typically improves children's school performance, such as higher family income, fewer children, better household infrastructure, and the ability to choose higher-quality schools. The authors suggest that these effects may be related to the transmission of cultural values, parental involvement, and the communication of maternal expectations and future aspirations regarding their children's educational achievement.

Our results corroborate the findings of Feijó, França and Pinho Neto (2022) and can be related to the social role usually attributed to mothers as the parent responsible for taking care of their children's educational development and to encourage them to complete their studies. Another important fact is that, in Brazil, more than 50% of the families are headed by the mothers, which highlights their role in the constitution of their children's Science Capital. In addition, it is important to highlight the homogeneity in the rates of parents who left school before the age of

16 across all levels of Science Capital, which points to the critical issue of school dropout among men—especially Black men—as previously reported by Ratusniak (2024).

Table 4 describes how the different genders are distributed among the three Science Capital levels. There are no significantly differences between the means of male and female students at $p < 0.01$ (low level: 24.9 (male), 25.1 (female); $F(10.988) = 0.087$; medium level: 45.5 (male), 45.3 (female); $F(10.963) = 0.039$). It was not possible to perform the statistical analysis at the high Science Capital level due to the small number of students at this stratum.

Table 4. Science Capital and gender (n = 936).

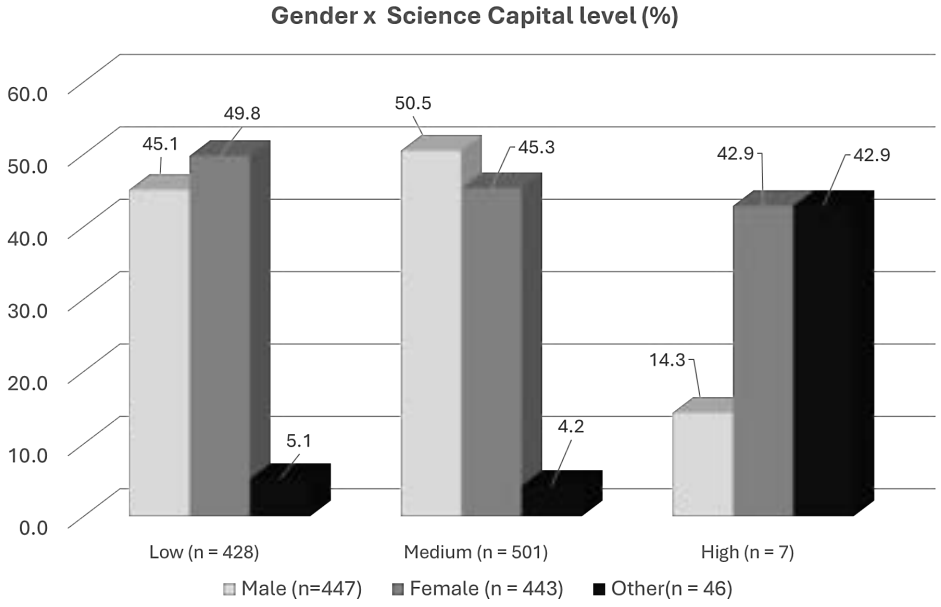
	Low (%)	Medium (%)	High (%)
Male	43.2	56.6	0.2
Female	48.1	51.2	0.2
Other*	47.8	45.7	6.5

* Other response/Preferred to not answer

It is noteworthy that a higher percentage of students with high levels of Science Capital did not identify themselves as male or female. However, further studies are needed to explore this finding, particularly given the small number of respondents in this group.

We have also analysed gender distribution in each Science Capital level (Figure 1). The result reinforces the small, non-statistically significant differences between the gender distribution at low and medium levels of Science Capital.

Figure 1. Distribution of the population by gender in each Science Capital level.



The influence of ethnicity on the Science Capital scores were also analysed and the results are described at Table 5.

Table 5. Science Capital and Ethnicity (n = 936).

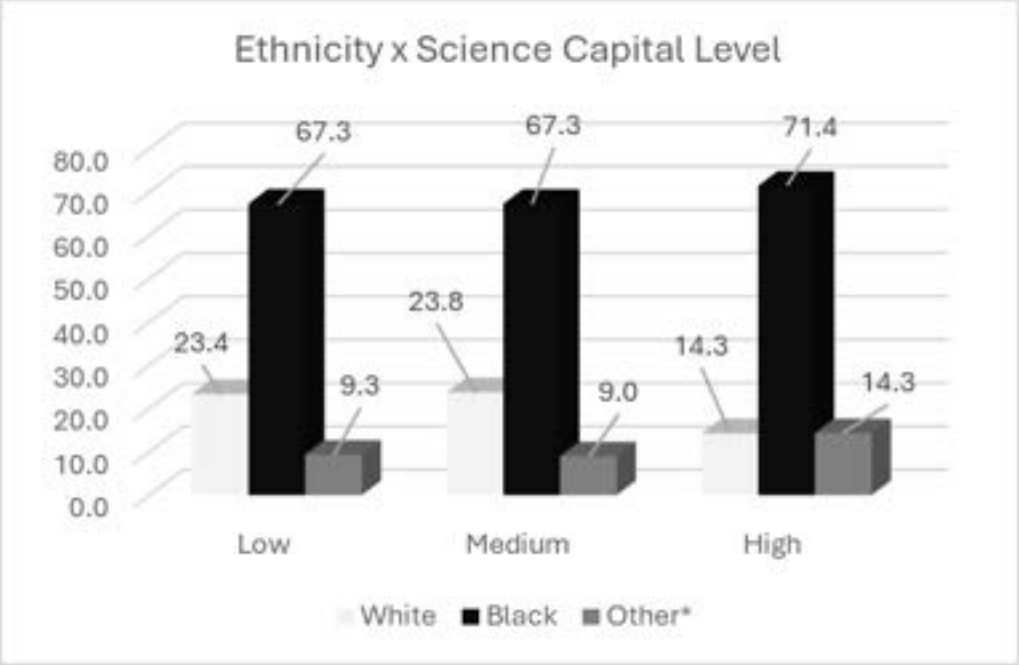
	Low (%)	Medium (%)	High (%)
White	45.5	54.1	0.5
Black	45.7	53.5	0.8
Other*	46.5	52.3	1.2

* Other response/Preferred to not answer

The data show similar distributions of White and Black students at the low and medium levels. At the low level, the means are not significantly different at $p < 0.01$ (25.3 (White), 25.0 (Black);

F(10.995) = 0.118) and the same is observed at the medium level at $p < 0.01$ (46.9 (White), 45.1 (Black); F(10.970) = 4.734). These data contrast with those obtained by Archer and colleagues (2015), in which ethnicity played an important role, a difference that may be associated with the different sample sizes of students in each ethnic group. On the other hand, we can infer the influence of low socioeconomic status, which, in these regions, does not differ greatly between these groups. These results are reinforced by the results depicted in Figure 2, showing that the ethnic distribution in each Science Capital level is similar to the ethnic distribution of the research population, as shown in Table 2.

Figure 2. Distribution of the population by ethnicity in each Science Capital level.



* Other response/Preferred to not answer

Conclusions

This study investigated the distribution of Science Capital among 936 high school students from public schools in the periphery of Rio de Janeiro and its correlation with sociodemographic variables. The results align with the international literature in one key aspect: the majority of students (53.5%) were concentrated at the medium level of Science Capital. However, our findings also reveal distinctive characteristics of the Brazilian context studied.

The most prominent factor associated with higher Science Capital was the mother's educational level, corroborating national research on the outsized influence of mothers on academic trajectories (Feijó et al., 2022). This underscores the crucial role of maternal cultural capital and involvement in fostering a scientific identity, especially in a social context where mothers are frequently the heads of households and primary educational guides.

Regarding gender, no statistically significant difference was found between the mean scores of male and female students. The higher percentage of gender non-normative students in the *high* Science Capital category demands deeper qualitative investigation to understand the specific trajectories and strategies of this group. Contrary to findings from Archer et al. (2015), ethnicity has not shown to be a statistically significant differentiating factor in this sample, suggesting that in these specific peripheral school contexts, with a high proportion of Black students, socioeconomic may override ethnic and gender distinctions in the formation of Science Capital.

These conclusions carry important implications for educational policy and practice: they reinforce the need for socioeconomic equity policies in science education, as this is strongly associated with gender and ethnicity in Brazil. Furthermore, they point to the potential of school-based interventions, such as science projects, to act as compensatory mechanisms for low familial Science Capital, particularly by connecting students with science professionals and career visions.

A primary limitation of this study is the extremely low percentage (0.7%) of students classified with high Science Capital, which restricts robust statistical analysis for this group. Future research should employ mixed methods, combining quantitative surveys with in-depth interviews and ethnographic observations. This approach would allow for a richer understanding of how Science Capital is mobilized, negotiated, and potentially resisted by students within their families and school environments, guiding the development of more effective and contextualized pedagogical actions.

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Inclusive Movement: Rethinking Physical Engagement In Science Classrooms

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Science education includes many physical learning activities designed to support learning. Students inevitably move when they participate in laboratory experiments, excursions, or if they are animated to move in a certain way that is supposed to promote learning. However, most research focuses on normative physical bodies and interpersonal relationships and thus unintentionally or implicitly excludes many students who are unwilling to perform certain actions as they may feel uncomfortable doing so. For instance, one may be an introvert and/or afraid of being observed. Some learners may have body-related trauma that makes them deeply distressed with certain activities, and others might simply be less athletic or less confident in taking up space than their peers. Finally, some bodies may be prohibited from performing certain actions due to physical disabilities. In this exploratory seminar, we invite researchers and educators who design physical activities of any form for students. Together, we explored what we need to know about students, and their bodies, for the design process, and what we can offer to students who might not be comfortable with the designed activity without isolating them.

Keywords: Embodiment, Inclusive Education, Science Education

Introduction

Physical engagement such as movement, gesture, and interaction is an integral part of science education. Students perform lab activities, they learn on excursions outside the classroom, or educators animate them to move in a way that promotes learning (e.g. Choudhary et al., 2019). Many scholars understand learning today as situated, active, and context-dependent (Nathan, 2021; Wilson & Clark, 2001), meaning that how students move and interact will affect learning.

Concurrently, science education aims to promote inclusion. Inclusion here denotes the "process of addressing and responding to the diversity of needs of all learners through increasing participation [...] and reducing exclusion within and from education" (UNESCO, 2005, p. 13). While studying the general effectiveness of interventions for the average student is crucial, scholars further ask for who under what conditions interventions may fail or even be harmful.

This seminar explored how scholars and educators may design physical activity inclusively. Specifically, we asked for whom a certain activity might create more stress as well as with whose bodies this activity is aligned and with whose not. For example, asking students to act as atoms and run faster when the temperature is higher is aligned with the bodies of students who can run (well), enjoy it, and feel comfortable about being perceived by others as well as interacting with them. We thereby build on work by Vickery and colleagues (2024) who found that students were aware of how their own and other students' bodies differ from a normative body and how this may affect learning experiences that involve physical activity.

In the following, we first pose the problem that this seminar aimed to address. Second, we provide a set of illustrative examples of empirical studies, which specifically target physical activity. Finally, we present the objectives and results of the seminar.

Learning And Physical Engagement

Conceptual Framework

Traditionally, separating body and mind was the common way to approach learning and educational practices. Fundamental learning theories like cognitivism by Piaget and behaviourism by Skinner overlooked their interconnectedness (Shapiro & Stolz, 2019). Later, Dewey suggested that students learn by interacting with the world (Dewey, 1986). Likewise, embodied cognition theories suggest that (inter)action influences cognition; therefore, meaning-making, problem-solving, and other cognitive activities are influenced by the learner's interactions with the world (Wilson, 2002).

In science education specifically, experimentation activities are a prominent example where students investigate phenomena by manipulating objects or materials while moving in a specific way (Hardahl et al., 2019). Furthermore, research shows that physical movement enhances science learning under the right conditions: for example, moving according to a predicted asteroid trajectory improved understanding of gravity and planetary motion (Lindgren et al., 2016), mixed-reality environments aided retention of centripetal force concepts (Johnson-Glenberg et al., 2016), and dance increased engagement with the periodic table (Solomon et al., 2022).

However, not all students are equally capable of or comfortable with physical and social activity (Spiel, 2021). Vickery and colleagues (2024) recently analysed fifth-grade students' reflections on their embodied modelling experiences. They found that the students saw tension between their non-normative bodies (e.g. physical dis/ability, or athleticism) and the normative expectations (e.g. moving around). The authors thereby pointed towards questions that we targeted in this seminar: for which participants might a certain activity create additional stress, with whose bodies is this activity aligned and with whose they are not? Are there other options for the latter?

Illustrative Examples: Interventions And Concerns Related To Physical And Social Engagement

Currently, research involving deliberate engagement of students' bodily movements primarily focuses on the effect of the interventions on learning and motivation, while students' willingness or concerns are seldom mentioned. In the following, we illustrate how such interventions might potentially intimidate or disadvantage certain groups of students by examining four studies, which involve social dynamics, educational technology, or direct embodiment. Importantly, note that we do not intend to criticize the study designs but to shed light on overlooked practical implications.

First, immersive tools and interactive platforms, while engaging, can pose challenges related to students' sensorimotor abilities. For example, in a study where students learned chemical concepts by using a haptic device providing force feedback (Müller et al., 2024), successfully navigating the device and interacting with virtual molecules was critical to learning. Furthermore, anecdotally, not all students experienced the force feedback from the haptic system equally. These differences might have had an impact on the effectiveness of the embodied activity. Similarly, in another study where students learned about derivatives in a VR environment, results showed that students with higher bodily awareness benefited more from the activity (Chatain et al., 2024). This discovery points to the need of designing for interactions that accommodate diverse bodily abilities.

Second, the social pressure inherent in classroom settings might put students into dilemmas when participating in embodied activities. For example, in the Energy Theater study (Scherr et al.,

2013), each student was “a unit of energy” and was required to use hand signs or move with their peers to a certain region to indicate the energy flow. In these activities, students may feel that their explicit movements are being observed by the group. They may then hesitate to participate in such learning activities due to a lack of confidence in their movements yet feel unable to opt out for fear of disrupting the group dynamic or being perceived as uncooperative. Therefore, educators and researchers might need to seek students’ consent in advance and implement facilitation strategies that acknowledge and address these social pressures.

Finally, direct embodiment helps students form a bodily representation of the concept but can also implicitly establish normative body shapes. For example, in a study where students learned about robot anatomy, teachers prompted them to dance alongside robots and think about the similarities between human and robot body structures (Zhang et al., 2024). This activity may be uncomfortable for some students, as it involves comparing their bodies to a normative ideal, represented by the robot’s form. We conjecture that students with physical disabilities might feel excluded. Other students who perceive their bodies as bigger, smaller, or simply different than the normative expectation may also feel self-conscious under constant comparison. Thus, these differences between the expected norm (in the case of this study represented by the robots) and the students' bodies need to be framed in a supportive and sensitive way.

Objectives

Immediate Outcomes

The primary aim of this exploratory seminar was for participants of this seminar to leave with heightened awareness of which parts of certain activities might create additional stress for which students and whose bodies certain activities are aligned with and whose are not. Furthermore, the participants should get ideas for alternative solutions for these students.

Together, we reflected on current design choices in science education that engage students' physical bodies and explore potential design guidelines to facilitate these choices. For example, how may we design alternative versions of an educational activity to include students with different bodies without alienating them? How can we build a trusting environment for students to be physically active? This seminar aimed to critically discuss such questions in the context of science education.

We created a short summary from two data sources. First, from group discussions, we gathered the physical mind maps that the groups created. Second, we took detailed notes during the whole-group discussion. From this, we identified three recurring themes:

First, a frequently suggested idea was designing **alternative options** inclusively for students who are unable or prefer not to participate in a certain activity. We can either co-design and negotiate alternative options with the students, or instructors can offer equally meaningful and important options (e.g., assigning the role of the observer but reframing it as an important part of an experiment).

Second, we discussed how to design **space and material** inclusively. We can avoid exclusion by communicating a certain activity ahead of time and thereby allowing students to prepare, e.g., by choosing appropriate/comfortable clothing. Furthermore, the use of manipulatives could replace body-based activities (e.g., using a fake hand instead of a physical one). Generally, creating a safe space (i.e., the physical learning space) in which students can also explore activities out of their comfort zone is important. However, we need to elaborate more on what a safe space fully entails and how to create it.

Finally, some participants stressed the importance of fostering a positive **attitude** towards new experiences. Specifically, we should encourage students to try activities that they may initially not be comfortable with. In other words, it is necessary to foster an open mindset towards new experiences. In this context, we can even further teach students how to deal with discomfort to a certain extent.

Expected Long-Term Outcomes

Since we were aware that a 45-minute session is not sufficient to conceive complete design guidelines, we facilitated the formation of research relationships among participants to further discuss science education research in the context of inclusive movement. We have since continued the discussion virtually with interested participants. Currently, as a group, we developed a leading question: what actions can teachers take to ensure inclusive scientific experimentation and how does this depend on context? We are preparing more contributions to the scientific discussion on inclusive science education by building on the outcomes of this seminar. This is a first step towards a more inclusive movement in science education, starting with a highly prominent form of movement – experimentation. Interested scholars and practitioners are invited to contact any of the authors.

Conclusion

This exploratory seminar highlighted the importance of inclusive alternatives, thoughtfully designed spaces and materials, and fostering an open mindset that supports students in engaging with new and potentially uncomfortable learning experiences. We hope that participants have left this exploratory seminar with heightened awareness of the diversity of human bodies in classrooms and empirical studies, and how they might stand in tension with the normative expectations of certain activities. We invite interested participants, graduate students, educators, and researchers to join our newly formed group by contacting any of the authors.

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Validation Of A Professional Science Identity Scale For Higher Education Students Of Chemistry

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Although wide-spread internationally, science identity is just recently gaining importance in higher education in Germany as a possible factor impacting retention rates in science study programmes. Since German language instruments for surveying higher education students' science identity are lacking, this study validated a scale for use in chemistry-related programmes. Areas of science identity negotiations were drawn from science identity theory following Carlone and Johnson (2007) and Hazari et al. (2010). From a review of existing English language scales, a science identity scale with references to science identity theory and professional aspirations was chosen and translated. Hypotheses concerning validity were formulated and tested. Evidence of face validity and content validity was collected by means of discussion with science education experts and in qualitative think alouds with Bachelor students in chemistry-related courses. A quantitative survey of Bachelor students in chemistry and primary science was used to examine convergent and differential evidence of validity. The study generated evidence for the validity of the scale for use with higher education students in chemistry-related programmes. In future studies with German-speaking students, the scale can be used as an indicator of professional science identity and its utility as a predictor of retention and completion of chemistry-related higher education courses can be examined.

Keywords: identity negotiation, measurement instrument

Introduction

Both numbers of enrolment in chemistry programmes and successful completions have been declining over the last decade (GDCh, 2024). While attrition and drop-out from higher education and their interplay with study-related variables have been studied extensively in the German context (e.g. Fischer et al., 2020), science identity has not yet been considered a possible predictor in chemistry. Even though developing a science identity is important for professional aspirations of science learners (Archer et al., 2015) and success in higher education (Carlone & Johnson, 2007), science identity is rarely studied in higher education in Germany (Borchert & Schwedler, 2024; Danielsson et al., 2023; Günter et al., 2023; Schmid, 2023).

Identity is often described as "[b]eing recognized as a certain 'kind of person' in a given context" (Gee, 2000, p. 99). These recognition processes are based on shared, normative expectations about what constitutes that kind of person (cf. virtual social identity, Goffman, 1963). Areas of negotiation of those identity norms in science are competence, performance, recognition and interest (Carlone & Johnson, 2007; Hazari et al., 2010). A science identity scale should therefore be able capture identity negotiations along these norms.

There are several English language measurement instruments for science identity, some focusing on specific subjects, e.g. chemistry (Wolfe, 2013; Hosbein & Barbera, 2020) or physics (Hazari et al., 2010; Wulff, 2019). Often a single-item indicator of seeing oneself or being seen as a science person is used, together with related scales for the areas of science identity negotiation (Archer et al., 2015; Hazari et al., 2010; Hosbein & Barbera, 2020; Schmid, 2023). Shorter scales combine the areas of negotiation (e.g. Wolfe, 2013), survey belonging to the community of scientists (Byars-Winston et al., 2016) or professional aspirations (Lockhart et al., 2022; Williams et al., 2018). However, there are no short instruments in German for professional science identity

in higher education. This study therefore validated a German translation of the scale by Williams et al. (2018) for use in chemistry-related courses.

Research Questions And Hypotheses

The science identity scale by Williams et al. (2018) addresses the areas of negotiation of science identity norms and professional aspirations by relating science identity to a professional future self. This focus is of interest to our intended use of the scale with higher education students as a predictor for attainment or drop-out (Beaujean, et al., 2025).

Validation of the German translation followed the research question: To what extent can the translated scale be used as an indicator of professional science identity (PSI) when administered to Bachelor students in chemistry-related study programmes with the aim to assess interindividual differences in the extent of PSI?

The validation process (Hartig et al., 2020) was guided by the following hypotheses:

H1: The score on the PSI scale is linked to the areas of science identity negotiation.

H2: Differences in scores on the PSI scale can in part be traced back to difference in the enrolment in a study programme.

Methodology

Translation And Think Aloud

The science identity scale by Williams et al. (2018; cf. Supplement 2) was chosen for translation to German. Its nine items each consist of a statement about the participants and their relation to science (e.g. Item 1: “I am the kind of person who can succeed in science”; German translation: “Ich bin so eine Person, die in den Naturwissenschaften erfolgreich sein kann”). Experts in chemistry education assessed whether the translation was idiomatic and consistent with the aims of the scale.

After revision of the translation, five Bachelor students in chemistry-related study programmes answered the items and commented on the scale in a think aloud study (Kansizoglu, 2024). Qualitative content analysis (Kuckartz & Rädiker, 2023) was used to analyse transcriptions of the audio recordings. The areas of science identity negotiation, “Competence”, “Performance”, “Recognition” and “Interest” (Carlone & Johnson, 2007; Hazari et al., 2010) were used as deductive categories for coding. The remaining data was coded inductively as fitting in with science (“Fit”) and job and career negotiations (“Aspirations”).

Collection Of Quantitative Data

In an online survey, the scale was administered to students in two chemistry-related Bachelor programmes (Chemistry and Primary School Science) during the summer terms of 2024 and 2025 at a German full university. The survey also contained established German language scales on interest in chemistry, chemistry self-efficacy and chemistry self-concept (van Vorst, 2013; cf. Schmid, 2023) for comparison to areas of science identity negotiations. All instruments were scored on a 4-point rating scale. Demographic data comprised age, gender identity, study programme, semester, academic generation, grade of school-leaving certificate and course profiles for chemistry.

Analysis Of Quantitative Data

Internal structure of the PSI scale was determined using exploratory factor analysis (EFA) with principal axis factoring and promax rotation (Weiber & Sarstedt, 2021). Parallel analysis was run

to determine factor structure (Weiber & Sarstedt, 2021) and reliability was calculated using Cronbach's Alpha.

In order to examine evidence for convergent validity (H1), the mean score on the PID scale was correlated with the mean scores on the scales for interest, self-efficacy and self-concept using Pearson correlation coefficient.

Differential evidence (Kline, 2016; H2) was examined by testing mean scores of PSI for differences between study programmes with the two groups of chemistry students and primary teacher students. The latter group studies general concepts of chemistry among other natural and social sciences in their education courses but does not participate in courses such as physical or organic chemistry. Therefore, lower scores on the PSI scale were expected for the primary science students than for the chemistry students. Since Shapiro-Wilk test indicated that data in the chemistry group were not normally distributed, differences were tested using Mann-Whitney U test.

Description Of Sample

The sample consisted of 133 participants. 36 were chemistry students and 97 primary teacher students. On average, the students were 22 years old and in their third semester. 94 students identified as women, 36 as men and 3 reported a non-binary gender identification. 71 students were first generation academics, 61 were at least second-generation academics.

Mean grade of school-leaving certificate ("Abitur", the grading system ranges from 1.0 (highest) to 4.0 (lowest passing grade)) was 2.2 ± 0.57. Regarding the course profiles for their school-leaving certificate, 23 students had studied advanced level chemistry, 46 basic level chemistry and 62 students had had no chemistry classes.

Results

Evidence Of Content Validity (H1)

In the think aloud study the students reported on their thoughts when reading and answering the PSI items. Evidence was found for all four areas of science identity negotiations. There were 16 codings addressing aspects of competence and 5 codings about performance in science. In 8 codings, recognition as a science person was expressed and 11 codings reported on student interest in science. The remaining data was coded inductively. There were 30 codings in which the students negotiated fitting in with science biographically and currently, while 21 codings dealt with their future job and career aspirations of becoming a science professional.

EFA with parallel analysis indicated an 8-item scale with one-factorial structure. Following EFA, item 9 was eliminated from the scale. Cronbach's Alpha of the 8-item scale was 0.895, indicating high reliability.

Convergent (H1) And Differential (H2) Evidence

Mean PSI score was found to correlate significantly and with a large effect size with interest in chemistry ($r = 0.667$; $p = .000$) and chemical self-concept ($r = 0.561$; $p = .000$) and with a medium effect size with chemical self-efficacy ($r = 0.423$; $p = .000$).

Chemistry students (MD = 3.6; IQR = 0.7; $n = 36$) scored higher on the PSI scale than primary teacher students (MD = 2.9; IQR = 0.6; $n = 97$) with a large effect size ($U = 555.550$; $p < .001$; $r = 0.52$).

Discussion And Conclusion

The study provides evidence of validity and reliability of the PSI scale for use with students in chemistry-related study programmes. Both hypotheses were supported by data analysis. Think aloud data further underpins that participants negotiate their identities against the norms of science identity and a professional self in science when answering the items.

Chemistry students score higher on the PSI scale than students of primary school science, indicating that the scale can distinguish students in degree programmes with varying importance of chemistry.

As sample sizes of the sub-groups differed, more data from students of chemistry need to be collected and confirmatory factor analysis needs to be run to assess factor structure in order to complete the validation process.

The PSI scale can be used as an indicator of professional science identity negotiations in higher education students. Its utility as a predictor of retention and completion of higher education chemistry programmes can be examined.

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Examining Cultural Influences On The Development Of Classification Among Indigenous Students

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In multicultural science education, classification is often treated as a neutral cognitive skill aligned with scientific taxonomy, while culturally embedded ways of organizing knowledge receive limited attention. Grounded in epistemological pluralism, a worldview perspective, and developmental psychology, this study examines how classification develops among Indigenous Tao learners and how cultural and experiential factors shape classification practices across age groups. Participants included Tao middle and upper elementary students and community elders. They completed a two-phase classification task involving living organisms, followed by semi-structured interviews. Data were analysed using an iterative coding scheme integrating theoretically informed categories with participants' sorting rationales and verbal explanations. Three interrelated patterns were identified. First, developmental shifts were observed in students' classification criteria, with upper elementary students demonstrating more stable use of biologically defined attributes and greater linguistic precision than younger students. Second, cultural influences on classification increased with age: elders consistently emphasized relational and ecological criteria grounded in lived experience, such as habitat and food chains, reflecting culturally embedded ways of knowing rather than less advanced reasoning. Third, instances of misunderstanding decreased over development and were primarily associated with early linguistic and conceptual instability, rather than cultural differences. These findings challenge deficit-oriented interpretations of Indigenous learners' scientific reasoning and reconceptualize classification as a developmental and culturally mediated practice. The study highlights the interaction of cognitive development, language, and worldview in shaping classification, and underscores the value of integrating Indigenous ecological knowledge within more inclusive approaches to science education.

Keywords: classification, developmental psychology, indigenous knowledge, epistemological pluralism, world view

Introduction

The Indigenous Tao people are a minority Austronesian group who migrated from Taiwan to the Philippines and later returned to a small island due to famine. Their culture, particularly fish taxonomy and dietary practices, differs significantly from scientific classification systems. However, this traditional knowledge is increasingly endangered, as modernization continues to replace indigenous ways of living. In formal schooling contexts, scientific taxonomy is often prioritized, while culturally embedded classification systems receive limited attention.

Previous empirical research in indigenous science education has demonstrated that learners' understanding of nature is not shaped solely by formal schooling, but is deeply intertwined with language practices, lived ecological experience, and culturally embedded knowledge systems. Evidence from longitudinal research involving Tao learners across age groups suggests that reasoning about living organisms consistently reflects relational and experience-based orientations, particularly in contexts where ecological interaction forms part of everyday life (Ge, 2022; Ge, 2023). At the same time, both local culture and school education play crucial roles in shaping students' understanding of scientific classification (Aikenhead & Jegede, 1999). In response to concerns about cultural erosion, the Taiwanese Ministry of Education has recently promoted culturally responsive curricula aimed at revitalizing indigenous knowledge. However,

how such cultural restoration efforts interact with formal science education remains insufficiently understood, raising important questions about how these frameworks coexist—or potentially conflict—in shaping students' learning experiences.

Classification is a fundamental and essential component of the Taiwanese elementary science curriculum at both middle and upper levels. Recent scholarship has emphasized that classification systems, like ethical judgments in science, are culturally mediated rather than universal, reflecting historically and socially situated ways of knowing (Castagno et al., 2023). From a worldview perspective, classification can be understood as reflecting underlying cognitive and cultural frameworks that organize how learners make sense of nature, rather than as an isolated cognitive skill detached from experience (Aikenhead, 2001). Although a small number of studies have explored how indigenous traditions and ways of thinking influence pupils' learning of taxonomy (Fu, 2004; Ge, 2023; Lee, Yen, & Aikenhead, 2012), classification as a developmental and culturally situated practice remains underexplored. In particular, empirical research examining how cultural influences shape the development of classification among Tao children is still limited. Greater attention to this issue may offer valuable insights for both science education research and policy initiatives within the Ministry of Education.

Research Questions

Accordingly, this study aims to explore the development of classification among Tao children across middle and upper elementary school levels, while also examining the extent to which cultural influences shape their classification processes. To address these aims, the study was guided by the following research questions:

1. How do Tao children at different elementary school levels classify living organisms in a sorting task?
2. What developmental shifts can be identified in Tao children's classification criteria across middle and upper elementary school levels?
3. How do cultural and ecological experiences influence Tao children's classification reasoning?

By situating classification within a worldview-oriented and epistemologically plural framework, this study seeks to contribute to a more nuanced understanding of how indigenous knowledge and formal science education interact in shaping children's scientific reasoning.

Theoretical Framework

In contemporary multicultural contexts, epistemological pluralism has increasingly been advocated as a way to challenge the exclusive representation of scientific knowledge in science education (Cobern & Loving, 2001; Sjöström, 2025). Grounded in theories from cultural anthropology and developmental psychology, this study examines the mechanisms underlying classification reasoning. From a worldview perspective, classification is not merely a technical or cognitive activity but reflects an organized framework of assumptions about reality. According to worldview theory (Kearney, 1984), people's ways of classifying the natural world are shaped not only by internal cognitive coherence, but also by ongoing interactions with, and adaptations to, their surrounding environments.

From a developmental psychology perspective (Bjorklund, 1995; Inhelder & Piaget, 1964; Vygotsky, 1962), although different theoretical traditions employ varying terminologies to describe cognitive developmental stages, they share the assumption that cognitive development unfolds over time. Early classification tends to rely on arbitrary or perceptual groupings, followed by organization based on relationships or associations, and eventually by categorization based on

shared attributes. While Inhelder and Piaget (1964) emphasized a relatively sequential progression aligned with cognitive maturation, Bjorklund (1995) and Vygotsky (1962) proposed more flexible developmental models that allow for variability across contexts and individuals. Importantly, Vygotsky (1962) argued that the development of classification is closely intertwined with language use, social interaction, and cultural participation, highlighting classification as a socioculturally mediated process rather than a purely logical operation.

Cultural influences on classification have been empirically demonstrated in cross-cultural psychology. For example, Ji, Zhang, and Nisbett (2004) found that Chinese participants tended to categorize objects based on relationships, whereas Western participants more frequently relied on shared attributes, suggesting that classification strategies are shaped by culturally patterned modes of reasoning and environmental affordances. More recent scholarship has extended this perspective by questioning the assumption that scientific knowledge—and the ethical judgments embedded within it—is epistemically neutral or culturally universal. Instead, ethics and knowledge practices are increasingly understood as culturally mediated, shaped by histories, epistemologies, and community practices (Castagno et al., 2023). From this viewpoint, tensions between Indigenous traditions and scientific knowledge are not merely ideological differences, but reflect encounters between distinct epistemological systems. Similarly, science learning has been conceptualized as relational, value-laden, and culturally situated, with knowledge produced through relationships among people, environments, histories, and purposes (Sjöström, 2025).

Research Method And Design

To investigate Tao children's classification patterns, this study employed a task adapted from Ji, Zhang, and Nisbett (2004). The task consisted of six sets of photo cards, each representing three common living organisms found on the island.

Phase I: Categorization Task

In the first phase, participants were asked to group two out of the three organisms together and explain the reasoning behind their choice. For example, if a participant grouped a pig and a monkey together while excluding a tree, stating that "both are animals," the response was coded as "characteristics" under the theme of "biological attributes" (as illustrated in Figure 1). Conversely, if a participant grouped a monkey and a tree together because "the monkey lives in the tree," the response was coded as "habitat" under the theme of "biological relations."

Phase II: Free Sorting Task

In the second phase, participants were instructed to freely sort all six sets of living organisms into groups based on their own criteria. To minimize linguistic influence, the selected organisms did not share any suffixes, affixes, or word roots in the Tao language.

Semi-Structured Interviews

In addition to the categorization task, participants took part in a semi-structured interview to assess their understanding of classification. At the beginning of the interview, they were asked whether they recognized the concept of classification. After completing the task, they were asked to reflect on whether their grouping decisions represented a form of classification

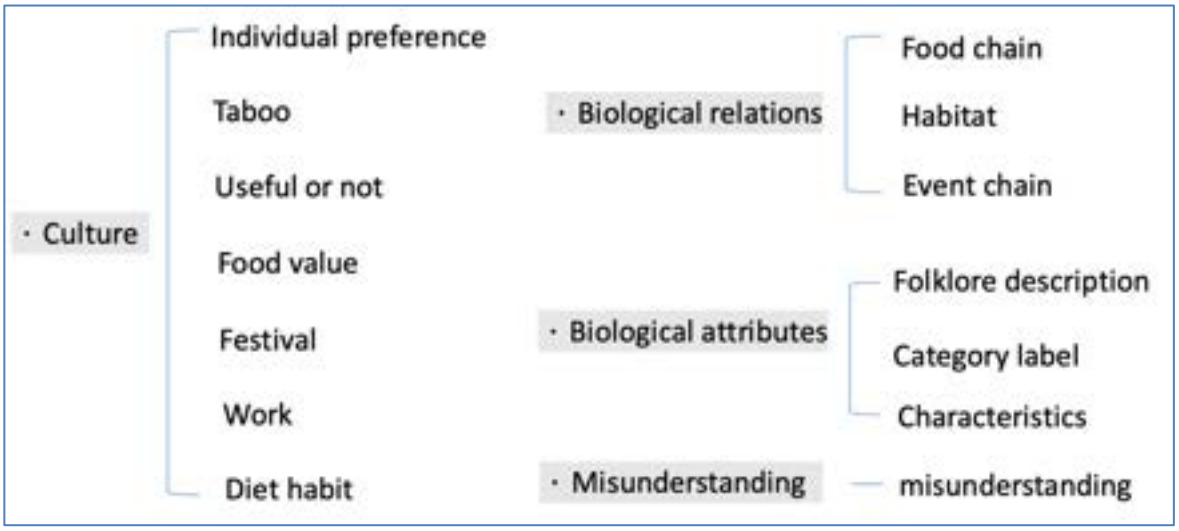
Data Analysis

Data analysis was guided by the study’s theoretical framework and research questions, drawing on perspectives from worldview theory and developmental psychology. The analysis aimed to examine how participants’ classification practices reflected both developmental patterns and culturally situated ways of reasoning. Rather than treating classification as a single outcome, the

analysis focused on the criteria and rationales participants used when grouping living organisms, as these were understood to index underlying cognitive, linguistic, and cultural orientations.

Participants' sorting decisions and verbal explanations were analysed iteratively. Initial coding focused on identifying the primary criteria used in classification, such as biological attributes and biological relations. These preliminary categories were informed by prior research on classification development and cross-cultural reasoning, providing an initial analytic lens for examining participants' responses. Comparisons were then conducted across middle elementary, upper elementary, and senior participants to identify developmental shifts and variations associated with age and lived ecological experience.

Figure 1. Coding scheme of classification criteria with 4 themes and 14 codes.



The coding scheme presented in Figure 1 was developed through an iterative process integrating theoretical perspectives and empirical data. As analysis progressed, participants' verbal explanations were closely examined to capture how classification criteria were articulated in practice. This process led to the refinement and expansion of coding categories, including the identification of culturally embedded reasoning, such as references to ecological practices, subsistence activities, and everyday experiences. Instances in which participants' explanations reflected ambiguous or inconsistent use of classification concepts were coded separately as misunderstandings, allowing analytic distinction between alternative epistemic orientations and conceptual confusion.

Consistent with a sociocultural perspective, participants' verbal explanations were treated as essential analytic data rather than supplementary comments. Attention was given to how language use, experiential references, and culturally grounded knowledge informed classification reasoning. Through this combined analytic process, the final coding scheme represents a synthesis of theoretical expectations and empirical regularities, providing a structured yet context-sensitive framework for interpreting classification as a developmental and culturally mediated practice within indigenous science learning contexts.

Participants

The study recruited both Tao elementary students and seniors as participants. Among the students, those in grades 3 and 4 were categorized as the middle school level group, while those in grades 5 and 6 were classified as the upper school level group. Table 1 presents the basic demographic information of the participants. Most of the senior participants had received a junior school education, while two had earned a bachelor's degree.

According to Table 1, the result that many students defined classification as waste sorting is related to Taiwanese waste management. Waste sorting has to be done before garbage disposal.

The data of seniors was drawn on previous study as reference so that the definition of classification and identification if their work is a kind of classification were not available in Table 1. Data analysis is based on the interview transcription and criteria of categorization. A coding scheme of 4 themes and 14 codes, shown as Figure 1, is developed for further comparison and analysis.

Table 1. Basic information about participants.

	number	gender	define classification	Is the work classification?
Middle elementary students	23	7 females 16 males	65% (n=15) waste sorting 13% (n=3) organize things 22% (n=5) sorting by common attributes	All confirmed
Upper elementary students	16	6 females 10 males	6% (n=1) unknown 44% (n=7) waste sorting 50% (n=8) sorting by common attributes	All confirmed
Seniors	24	12 females 12 males		

Findings And Discussion

The findings are presented with respect to three interrelated themes: developmental shifts in classification criteria, the increasing salience of cultural influences with age, and the reduction of conceptual misunderstanding over development.

I - Developmental Shift In Classification Criteria

Students' classification performances revealed clear developmental patterns that align with, but also extend, perspectives from developmental psychology. As shown in Table 2, upper elementary students were more likely to classify living organisms based on biological attributes (61.5%) than middle elementary students (49.4%) in Phase I. This pattern is consistent with developmental accounts suggesting that increasing cognitive maturity supports more stable use of attribute-based categorization. At the same time, the frequent misuse of terminology among middle-level students—for example, using "living things" to refer specifically to "animals"—indicates that younger students' classification reasoning is closely intertwined with ongoing language development. Classification at this stage appears to rely not only on perceptual features, but also on emerging linguistic resources that constrain how biological categories are expressed and differentiated.

In contrast to students' predominant reliance on biological attributes, seniors consistently classified organisms based on biological relations, such as habitat, food chains, and ecological interactions, across both Phase I and Phase II (Tables 2 and 3). Interview data revealed that many seniors explicitly drew on lived experiences of survival on the island, including fishing practices and long-term interactions with local organisms, when explaining their sorting decisions. Rather than indicating a less advanced form of classification, this relational pattern reflects an experience-driven mode of reasoning grounded in sustained engagement with the external environment. From a worldview perspective, seniors' classifications can be understood as the outcome of accumulated ecological knowledge, in which relationships among organisms are more salient than abstract categorical boundaries. This finding challenges a strictly linear interpretation of classification development and supports sociocultural models that emphasize variability in developmental trajectories shaped by experience and environmental adaptation.

Results from Phase II further illuminate the interaction between development, language, and classification. When participants were provided with a wider range of biological vocabulary, such as reptile categories, upper-level students demonstrated improved linguistic precision in their explanations. However, the overall reliance on biological attributes remained relatively consistent between middle and upper elementary students (Table 3). This suggests that while language development enhances students' ability to articulate classification decisions, it does not necessarily shift their underlying classification orientation. Developmental change in classification thus involves not only cognitive maturation, but also the expanding availability of linguistic and experiential resources that shape how classification criteria are selected and justified.

Table 2. Criteria of classification-the themes appear in Phase I.

Theme	Middle level students	Upper level students	Seniors
Culture	4.0%	6.3%	23.1%
Biological relations	25.0%	31.3%	63.9%
Biological attributes	49.4%	61.5%	9.5%
Misunderstanding	21.6%	1.0%	3.4%

Table 3. Criteria of classification -the themes appear in Phase II.

themes	Middle level students	Upper level students	Seniors
Culture	5.0%	11.2%	24.5%
Biological relations	31.5%	32.2%	55.0%
Biological attributes	50.8%	50.0%	19.9%
Misunderstanding	12.6%	6.6%	0.7%

Importantly, evidence beyond the sorting tasks further supports this interpretation. Interview data from a parallel longitudinal project (MOST 111–MY2) revealed convergent reasoning patterns, in which Tao participants across age groups consistently framed living organisms through relational, ecological, and culturally embedded explanations. This cross-task consistency indicates that the observed classification patterns reflect relatively stable epistemic orientations rather than task-specific strategies. Taken together, these findings suggest that differences between students' attribute-based classifications and seniors' relational classifications are best understood not as developmental deficits, but as distinct ways of organizing biological knowledge shaped by language development, lived experience, and culturally grounded worldviews.

II-Cultural Influence Increases With Age

Beyond developmental shifts in classification criteria, the findings indicate that cultural influences on classification become increasingly salient with age. As shown in Tables 2 and 3, seniors demonstrated the highest proportion of culturally grounded classification, frequently drawing on traditional ecological knowledge, subsistence practices, and culturally meaningful relationships among living organisms. In contrast, cultural references were comparatively rare among middle and upper elementary students, whose classifications were more strongly anchored in biologically defined attributes. This age-related pattern suggests that cultural knowledge does not merely coexist with scientific classification but progressively shapes how classification criteria are selected and prioritized over time.

From a worldview perspective, this pattern aligns with Kearney's (1984) assertion that classification systems reflect organized cognitive frameworks shaped through ongoing

interaction between individuals and their environments. Seniors' reliance on cultural reasoning indicates that classification is not simply a cognitive operation applied to biological entities, but a practice embedded within socio-cultural histories and lived ecological experiences. Cultural knowledge in this context functions as an interpretive framework that foregrounds relationships, purposes, and ecological interdependence, rather than abstract taxonomic boundaries.

These findings also resonate with research in cultural psychology demonstrating systematic differences in categorization strategies across cultural contexts. Ji, Zhang, and Nisbett (2004), for example, found that individuals from East Asian cultural backgrounds tend to emphasize relational classification, whereas Western participants more often rely on categorical attributes. The Tao seniors' classification practices extend this line of research by illustrating how relational and culturally embedded reasoning is not only culturally patterned, but also developmentally reinforced through long-term participation in local ecological and social practices. Taken together, the results suggest that indigenous classification systems represent integrated ways of knowing that connect biological understanding with cultural meaning, rather than deviations from scientific classification norms.

III-Reduction In Misunderstanding Over Development

In addition to developmental shifts and increasing cultural influence, the findings reveal a clear reduction in misunderstanding across age groups. As shown in Tables 2 and 3, instances coded as misunderstanding were more prevalent among middle elementary students and decreased substantially among upper elementary students and seniors. This pattern suggests that conceptual confusion in classification is not a stable characteristic of indigenous learners' reasoning, but rather a transitional phenomenon associated with early stages of cognitive and linguistic development.

Closer examination of students' explanations indicates that misunderstandings among younger participants often stemmed from limited linguistic resources and incomplete differentiation of biological categories, rather than from culturally grounded ways of knowing. For example, the use of overly general terms or inconsistent category labels reflected difficulties in articulating classification criteria, rather than alternative epistemic orientations. As students gained greater linguistic precision and conceptual stability, such ambiguities diminished, even as cultural or relational reasoning did not necessarily increase in the same way. This distinction is analytically important, as it underscores the need to differentiate between misunderstanding as conceptual instability and culturally embedded reasoning as a coherent way of organizing knowledge.

From a sociocultural and worldview perspective, the reduction of misunderstanding over development further supports the interpretation that indigenous learners' classification practices are shaped by expanding linguistic, cognitive, and experiential resources. Seniors' near absence of misunderstanding, alongside their strong reliance on relational and ecological criteria, indicates that culturally grounded classification is not a less developed form of scientific reasoning, but a stabilized epistemic orientation supported by extensive lived experience. Taken together, these findings suggest that effective science education in indigenous contexts should not aim to replace cultural ways of knowing, but to support learners in developing the linguistic and conceptual resources needed to navigate and articulate multiple classification frameworks.

Conclusion

This study examined the development of classification among Tao learners across middle and upper elementary school levels, with particular attention to how developmental, linguistic, and cultural factors shape classification practices. By integrating perspectives from developmental psychology, worldview theory, and epistemological pluralism, the findings offer a nuanced

account of classification as a culturally mediated and developmentally situated practice rather than a purely technical cognitive skill.

Across the findings, three interrelated patterns emerged. First, developmental shifts in classification criteria revealed that students increasingly relied on biologically defined attributes as cognitive and linguistic resources expanded, while seniors predominantly emphasized relational and ecological criteria grounded in lived experience. These patterns align with developmental theories yet also extend them by demonstrating that relational classification among elders reflects stabilized ecological knowledge rather than a less advanced stage of reasoning. Second, cultural influences on classification became more salient with age, as seniors' classifications drew extensively on traditional ecological knowledge and culturally meaningful relationships among organisms. From a worldview perspective, these findings highlight how classification functions as an epistemic practice shaped by sustained interaction with specific environments and cultural histories. Third, the reduction of misunderstanding over development underscores the importance of distinguishing conceptual instability associated with early language development from culturally embedded ways of knowing. As linguistic precision and experiential grounding increased, misunderstandings diminished, while culturally grounded classification orientations remained coherent and stable.

Taken together, these findings challenge deficit-oriented interpretations of indigenous learners' scientific reasoning and instead support a view of classification as a practice that emerges through the dynamic interplay of cognitive development, language use, and cultural participation. For science education, particularly in multicultural and indigenous contexts, this study suggests the value of pedagogical approaches that do not seek to replace indigenous ways of knowing, but rather support learners in navigating and articulating multiple classification frameworks. By recognizing relational and ecological reasoning as legitimate forms of scientific sense-making, science education can move toward more inclusive and contextually responsive practices.

Limitations And Future Research

Several limitations of this study should be acknowledged. First, the classification tasks employed in this research focused on living organisms within a specific ecological and cultural context. While this design was intentional and theoretically grounded, the findings may not be directly generalizable to other indigenous groups or scientific domains without further investigation. Second, although the study incorporated multiple data sources, including sorting tasks and interviews, the analysis relied primarily on qualitative coding of participants' explanations. Future research could complement this approach with longitudinal designs or mixed-method analyses to examine how classification practices evolve over time within individuals.

Future research could also explore how instructional interventions explicitly designed to bridge indigenous and scientific classification systems influence students' reasoning and language use. Comparative studies across different indigenous communities would further illuminate how diverse ecological contexts shape classification practices and worldview orientations. Finally, extending this line of inquiry to classroom-based interactions could provide deeper insight into how teachers and students negotiate multiple epistemic frameworks during science learning. Such research would contribute to ongoing efforts in science education to develop culturally responsive pedagogies that respect epistemological diversity while supporting students' scientific understanding.

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Positioning Towards Science From An Identity Perspective: Results Of An Interview Study With Pupils In Their Initial Science Lessons

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The identity perspective is one way to better understand educational choices. Against this background, pupils' perceived approaches to science and their first institutionalised encounters with science, for example in subject lessons, can provide initial indications of their educational decisions throughout their educational careers. The aim of this research project is to gain a better understanding of how grammar school pupils perceive and position themselves in relation to science and science lessons, particularly in physics and chemistry during their first two years of science education. Guided and narrative-based individual interviews were conducted in two German federal states and 15 different grammar schools. The interview study comprises two waves of data collection, with all learners having experienced at least one school year of physics lessons at the time of the first interview. In a first step we focus our analysis on understanding which aspects students use to position themselves in relation to science and physics in their first interview. The qualitative content analysis of 30 interviews led to the development of a category system with four main categories: personal characteristics, school biography, science (subjects) and physics (lessons). The analysis reveals that students primarily position themselves on the basis of the science lessons they have experienced. The four main categories also correspond to core areas of students' (science) identity development.

Keywords: Early Science Education, Qualitative Research, Science Identities

Introduction

According to international science education research, educational choices, such as the decision to engage with or distance oneself from science, or the experience of feeling included in or excluded from scientific communities, can be understood in relation to identity (Archer et al., 2010; Carlone & Johnson, 2007). A preliminary understanding of identity can be drawn from socio-psychological and sociological perspectives: identity formation involves both self-knowledge and self-image, as well as the perceptions and ideas developed through interactions with others (Morf, 2023; Shanahan, 2009). Therefore, identity construction can be seen as a negotiation process influenced by an individual's social context and embedded within broader societal frameworks (Regan & DeWitt, 2015).

Theoretical Background

In the research project IdentMINT the construct of identity is employed as a multi-perspective framework to analyse students' engagement with and positioning towards science. Our identity framework focuses on students as whole persons, rather than isolating individual educational constructs (Avraamidou, 2020; Rabe & Krey, 2018), thereby placing their self-perception and relevance systems at the center of the inquiry.

Numerous studies have explored science identities and found that gender, ethnicity, and socio-economic background significantly influence educational trajectories (e.g., Archer & DeWitt, 2015; Hazari et al., 2022; Holmegaard et al., 2014; Kessels et al., 2006). However, there remains a research gap regarding how introductory physics and chemistry education shapes identity negotiation (Rabe & Krey, 2018). This is especially important given that, in many countries, including Germany, institutional encounters with science coincide with adolescence, a critical

phase of identity development. A developing physics identity may conflict with other identities, such as a students' gender identity (Brickhouse et al., 2000).

Positioning is regarded as a relational construct and constitutes an integral part of human communication and understanding (e.g. through actions, speech acts or social interaction). It assigns a relational position to both persons and objects in social space, either explicitly or implicitly (Davies & Harré, 1990; Harré & Van Langenhove, 1991). In the research project IdentMINT, positionings are reconstructed from linguistic expressions, i.e. statements made by learners about an object, and are regarded as indicators of identities. This understanding aligns with Harré and Van Langenhove (1991), who emphasise that narratives in which people talk about themselves differ according to how the individuals wish to present themselves.

Research Interest

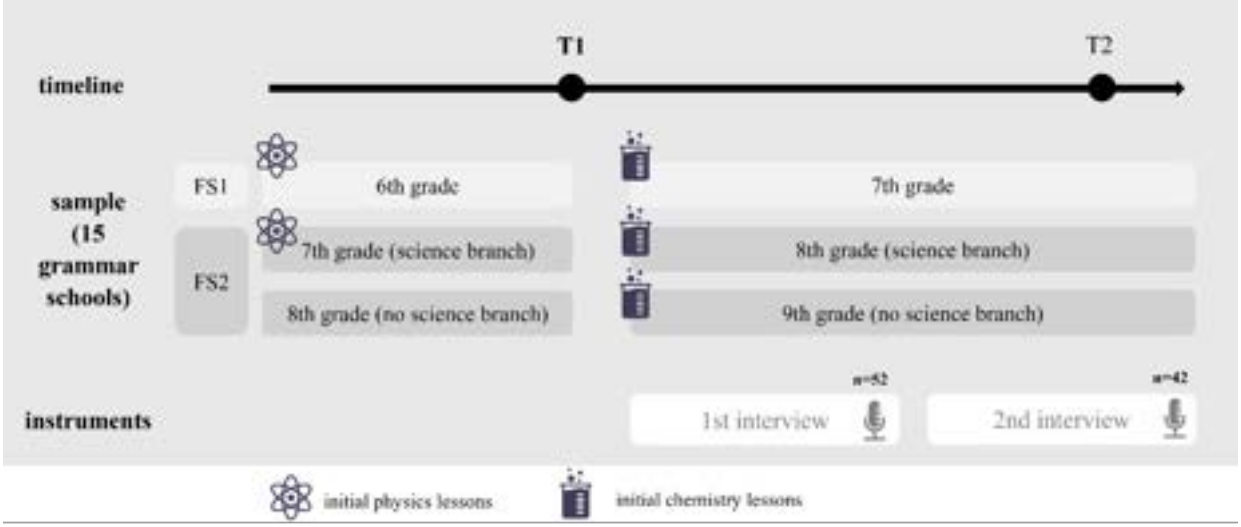
In Germany, science education is based on subject-specific lessons like physics, chemistry and biology, rather than an integrated subject "science". The goal of IdentMINT is to deepen our understanding of how grammar school students perceive and relate to science, particularly in physics and chemistry, during the initial years of their formal science education. The central research question is: How do young learners position themselves towards science, particularly physics and chemistry, when talking about it?

Study Design And Interview Sample

The research project employs a mixed-methods approach, combining the interview study presented in this article with a longitudinal questionnaire survey.

Narratives, in which students shed light on their own experiences, offer valuable opportunities for identity formation (Lucius-Hoene & Deppermann, 2002). Accordingly, guided, narrative-based individual interviews were conducted with students from fifteen different grammar schools across two federal states of Germany (FS1: Saxony Anhalt, FS2: Bavaria). The interview study comprises two data collection points (T1 and T2). By T1, all participants had completed at least one year of physics education and by T2, they had additionally completed one year of chemistry (see Figure 1). However, the present article reports only findings from interviews conducted at T1.

Figure 1. Overview of the longitudinal interview study design.



The interview sample was selected to be as heterogeneous as possible with respect to gender, ethnic background and migration history, interest in science, and Science Capital. The relevant school authorities have approved the data collection from an ethical and legal perspective. The sole requirement for participation was voluntary consent, authorized by the participants' legal

guardians. At T1, the sample comprised 52 students from grades 6 and 7 (FS1) or 7 to 9 (FS2), 42 of whom also participated at T2.

Data Analysis And Findings

To answer the research question, the interviews were analysed using qualitative content analysis (Kuckartz, 2018). The category system was developed on the basis of a reduced sub-sample of 30 learners, selected to ensure broad coverage of the aforementioned characteristics. The category development followed a combined deductive-inductive approach: initial categories were derived deductively from the interview guideline and the theoretical and empirical literature in the field. The categories were subsequently refined and specified inductively based on the interview transcripts. Throughout the analysis process, intercoder agreement is regularly assessed; so far, a 'substantial' level of agreement has been achieved with k_n= 0.73 (Brennan & Prediger, 1981). The developed category system will be applied to the remaining 22 interview transcripts and revised if necessary. Below, we will provide an illustrative insight into the category system, including selected illustrative examples.

Insight Into The Category System

As a first result, we identified four main categories, along with their respective subcategories, which highlight key aspects that students use to position themselves in relation to science:

- *Personal Characteristics* (e.g., self-attributed qualities, hobbies, career aspirations, role models, health-related aspects)
- *School Biography* (e.g., favourite subjects, influential people at school, transition from elementary to grammar school, school choice, selection of subject focus)
- *Science (Subjects)* (e.g., associations with science (subjects), general interest in science, extracurricular engagement with science, science-related activities at home)
- *Physics (Lessons)* (e.g., engagement with physics (lessons), comparisons with other subjects, attribution of ability, significant others in relation to physics (lessons), gender stereotypes in physics, factors leading to rejection)

Revealing information about oneself – such as discussing hobbies or career aspirations – can involve an explicit or implicit act of positioning in relation to science. Statements that provide such information have been assigned to the *Personal Characteristics* category.

Similarly, discussion of one's own school biography was identified as a form of positioning. Narratives about favourite subjects or the choice of grammar school often reflect positionings towards science that were therefore assigned to the *School Biography* category.

It is also noticeable that the learners tend to express themselves in a more vague and distant manner when referring to science in general compared to physics, chemistry, and biology. In their narratives, they predominantly draw on experiences from subject-specific lessons. To illustrate these subject-specific modes of positioning, we present examples from the following subcategories of *Physics (Lessons)* category:

- *Physics in Comparison with Other Subjects*,
- *Significant Others in Relation to Physics and Belonging*, and
- *Attribution of Ability*.

One common form of positioning is comparing physics with other subjects. Students typically identify a characteristic of physics and relate this characteristic to themselves. The following

excerpt from the interview with Ajala (pseudonyms are used) illustrates such a comparison, in this case between the subject of physics and German:

> "Physics also has its grammar, or something like that. In other words, [also in physics] there are things you must be able to do or know ways how you should approach it. In German, however, one can talk […]. German also has a gut feeling. You can answer something with a gut feeling, but in science it's just facts and you must be able to justify them and so on." (Ajala, grade 8; Pos. 167)

A second subcategory captures forms of positioning through significant others and a sense of belonging. Students position themselves in relation to physics by referring to people associated with this subject. For example, Latif emphasises his passion for physics to set himself apart from his classmates:

> "I would like to talk about physics, but I don't exchange ideas much, actually not at all, because I don't think my classmates are very interested in it. Or they just don't care or don't want to talk about class. Maybe it's boring for them." (Latif, grade 7; Pos. 155)

Finally, pupils also position themselves in relation to science by means of ability attributions. They describe their perceived skills, challenges in physics and strategies for handling physics tasks. Elza, for example, talks about her confidence when experimenting in physics:

> "Yes, I really like experimenting because you can somehow better understand the whole thing working, so much better than when someone describes how the experiment should have gone or when the teacher demonstrates it in front of you. So, when you experiment yourself, it's just somehow cooler and more practical." (Elza, grade 9; Pos. 105)

Case Analysis – An Example

A second finding is that positioning is highly individual, particularly within these subject-specific modes of positioning. To illustrate this, we present several examples from a single student, Laila.

At the time of the first interview, Laila was in grade 8 and had chosen the science profile at her grammar school. With the start of the new school year, she was placed in a new class, which was challenging for her because she had to make new friends. All her previous friends selected the language branch and are therefore in other classes. When asked why she chose the science branch, Laila expressed a generally positive view of science, presenting herself as a student interested in chemistry and capable of meeting the performance expectations in both chemistry and physics. However, in retrospect, it is evident that she had not anticipated experiencing difficulties with physics:

> "So, for me, it was clear that I would take the science branch. Because I simply wanted to have chemistry lessons as soon as possible, and I find it difficult to learn languages, so the idea of writing school assignments in chemistry and physics, that wouldn't bother me so much (laughing). Except that I already have a few problems with physics. But otherwise, it was an easy decision for me to choose science." (Laila, grade 8; Pos. 47)

When asked about her experiences in physics, she positions herself as 'not a big fan':

> "Oh, (laughing) physics. So, I'm not a big fan. So, at first, when we started, I think last year, I really tried to have fun and so on. So, the topic of light, I had some fun, because there were lots of activities and experiments and doing, and observations. But NOW there are just formulas, and lots of mathematics. And I don't like maths at all. For me, so to speak, physics is now a second maths." (Laila, grade 8; Pos. 67)

Her explanation highlights her conflict with physics: although she enjoys certain topics and scientific activities such as experimentation and observation, the mathematical nature of physics poses a challenge for her. As a result of her experiences in physics lessons, the subject feels like a second mathematics class, which is particularly significant because she dislikes mathematics. Nonetheless, her belief that physics should be enjoyable remains evident.

Her favourite subject at school is a science subject: biology. In the following interview excerpt, she emphasizes the personal relevance and her interest in biological topics, particularly in plants:

> "I like those [biological] topics, they are very interesting. It's fascinating to observe other living beings and see what they do. This is a new world, and I think that's really, really nice. Also taking care. Even if it's just breathing or something, or like plants, just standing (laughing) there. They are also very interesting, because they are simply different. Taking a closer look, has always appealed to me, so to speak." (Laila, grade 8; Pos. 59)

Lailas mother, a geriatric nurse, supports her interest in plants by sharing her knowledge and providing books. In her leisure time, Laila also watches documentations about animals and enjoys drawing characters and stories. After school, Laila spends most of her time at home and rarely meets with friends. She lives with her parents and younger sister, and she considers her mother a role model. Her parents encouraged her to go to grammar school after primary school to ensure she received the best possible education. At the beginning of the interview Laila expressed her desire to become a plant or animal researcher, conducting experiments or observe whether animals can think independently.

Summary And Implications

The category system indicates that students primarily position themselves based on their experiences in science lessons, alongside personal and school-linked factors. While some students reflect on more general scientific experiences, they often illustrate their positioning with concrete subject-specific encounters. The question of why certain aspects are addressed by the interviewees will be explored in an exemplary, reconstructive, in-depth case study.

Main Categories As Core Areas Of (Science) Identities

When learners discuss physics, they refer not only to physics aspects but also to personal and school-related factors, such as being a good student, friendships, or engaging in hobbies. Our analyses suggest, consistent with previous research, that identity negotiations in physics are intertwined with broader identity processes and cannot be considered in isolation (Calabrese Barton et al., 2013; Hazari et al., 2010). Accordingly, the four main categories represent core areas of students' (science) identity development.

In the interview example with Ajala, she identifies structure and rules, or as she calls it a specific "grammar", in both German and physics. However, she values rational justification in physics more than an intuitive approach she experiences in German. By comparing the two subjects, Ajala reveals a facet of her identity through her positioning. Latif faces the challenge of wanting to discuss physics but is struggling to find like-minded peers, as his classmates are less interested in the subject. This sense of uniqueness shapes his positioning. Elza, in contrast, demonstrates self-confidence in experimenting and trusts her ability to acquire knowledge through hands-on activities. The influence of significant others and the importance of group affiliation (illustrated by Latif's experience) align with previous research, which emphasize the role of these factors in identity formation (DeWitt & Archer, 2015). Furthermore, the data suggest that access to science education plays a crucial role in shaping students' engagement with science (subjects) and in the negotiation of their identities.

Science Identities?

Furthermore, students differ considerably in whether they perceive science as a cohesive whole or as a collection of distinct disciplines. References to chemistry are particularly notable, given that, at the time of the first interview, the students had attended no or only a few weeks of chemistry instruction. It should be noted at this point that at the participating schools there is no subject called "science", which complicates discussions of a general science identity. Future research could investigate the validity of assuming the existence of a general science identity versus distinct identities for physics, chemistry, or biology, especially for specific educational purposes. This is particularly evident in Laila's interview. While she demonstrates an ambitious and open-minded stance towards science in general and biology in particular, she struggles with physics at grammar school. Although she initially looked forward to physics with high expectations and continues to enjoy scientific activities, she has distanced herself from physics due to its mathematical emphasis. This case raises a larger question: How does the development of subject-specific identities might align with or conflict with the development of broader scientific identities? It is crucial to empirically investigate the impact of integrated science teaching versus discipline-specific instruction on students' identity development.

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Identifying And Understanding Factors Influencing Students' Decisions Regarding STEM Education Pathways – First Findings

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The research project DynaMINT (Dynamics of STEM-related educational and vocational decisions of children and adolescents) investigates how the self-positioning of children and adolescents towards science, technology, engineering and mathematics (STEM) develops during adolescence (age 13 to 16). This longitudinal study surveys participants over a period of 18 months.

The qualitative study aims to identify factors shaping students' decisions for or against STEM educational pathways, particularly in grade nine and ten. The study examines negotiation processes connected to STEM identity development and how co-curricular and informal STEM activities influence these processes with the goal of a clearer understanding of students' educational decision-making in STEM contexts.

By incorporating longitudinal data collection methods, including interviews and short surveys, the research will provide valuable insights into how students' perceptions of STEM evolve over time. This article presents the theoretical framework, the methodological approach, and first findings with a focus on two case studies.

Keywords: Science Identity, Qualitative Research, Educational Pathways

Introduction

Due to its crucial role in driving innovation, economic development, and addressing complex societal challenges, there has been an increasing global emphasis on STEM education (OECD, 2018). However, participation in STEM subjects remains lower than desired, especially among certain demographic groups, including women, students from lower socioeconomic backgrounds, and those from underrepresented minorities (Anger et al., 2024). At the end of secondary school, German students are at a crossroad in their educational journey, making decisions that will shape their academic and professional futures (Kultusministerkonferenz, 2022). Understanding the factors that influence these decisions can provide valuable insights into how to encourage more students to pursue STEM pathways.

Students' Decisions On Educational Pathways

Educational pathway decisions are shaped by a complex interplay of social, cultural, and institutional factors (Rabe und Krey, 2018). In Germany, early educational tracking requires students to choose between different types of secondary schools, which structure subsequent subject choices and educational opportunities (Kultusministerkonferenz, 2022). Within those school-types students have the possibility to decide on different subjects or different foci (e.g. science-focused or focused on foreign languages).

Besides these institutional aspects, the socioeconomic status and the parents' educational level still play a significant role in the students' decision-making process in Germany. Adolescents whose parents attained a lower educational status are less likely to finish their school career with a certificate that allows them to go to university than children of parents with a higher educational status (Autor:innengruppe Bildungsberichterstattung, 2024). Additionally, socioeconomically disadvantaged students are on average seven times less likely to reach the basic level of

competence in mathematics and science than socioeconomically advantaged students (OECD, 2023).

As can be inferred from the complex interplay of the factors mentioned above, the choice of educational pathways is a process that has no defined beginning or end. „Who one is and who one desires to be […] is always under negotiation and is contingent upon the resources one has access to and the social, cultural, and historical context in which one seeks to author oneself with and against the expectations of others" (Calabrese Barton et al., 2013). In other words, every decision for or against an educational pathway is a negotiation process, that is formed by and in turn forms the student's identity.

Negotiation Processes Within The Framework Of STEM-Identity Development

As the focus of the study lies on negotiation processes regarding STEM in general and on STEM subjects, the research is based on the science identity construct. Science identity research constitutes a broad international field (Danielsson et al, 2023) and provides a suitable framework for integrating multiple perspectives on educational decision-making in STEM. Kang et al. (2019) address how young people come to perceive both their present selves and possible future selves in STEM. Furthermore, the focus can be directed away from the individual towards social, political or even cultural perspectives. For example, what makes a promising STEM learner? Do these factors apply to all learners in this environment? Which factors inhibit or promote learners? (Carlone, 2023; Van Tuijl, 2016)

We focus on two models within this context: 'Framework of students' identification with physics' by Hazari et al. (2010) and 'A model of factors shaping young people's science aspirations and identities age 10-19' by Archer et al. (2020) To use these models in our research, we adapted them to the broader field of STEM-identity.

Hazari et al. (2010) who based their 'Framework for students' identification with physics' on the Model of Carlone and Johnson (2007), define identity as an interplay between three aspects: the personal, the social and the role identity. All those aspects influence each other and affect the student's view on physics. A student's development of their physics identity, which is one role-identity, is shaped by their personal and social sense of self, along with their physics-related perceptions. Four indicators for this perception are: interest (desire to learn and engage with physics), competence (belief in understanding physics), performance (belief in completing physics tasks), and recognition (acknowledgment as a physics person) (Hazari et al., 2010).

Archer et al. (2020) describe the influences on science identity and aspiration in an encompassing model which considers the overall influence of structural inequalities of gender, ethnicity and social class. Further, they name capital related inequalities (e.g. Science Capital or specific risks like mental health issues), educational factors and practices (e.g. careers education, the role of teachers or educational gatekeeping) and the representations of science (e.g. portrayal of science as masculine and clever).

Further aspects shown to influence science identity development are Significant Persons (parents, guardians, friends, teachers, siblings and well-known personalities from the media (Sjaastad (2012)), Critical Moments (events, that are retrospectively mentioned by students to have had a high impact on their decision towards STEM (Lykkegaard & Ulriksen, 2019)) and co-curricular STEM-activities (Mohr, 2022).

Co-curricular STEM Activities, Informal STEM Activities And Career Education

Co-curricular STEM activities are understood in this research as school-organized activities conducted outside regular lessons and facilitated by non-teaching staff (e.g. out-of-school

laboratories, factory tours, visits to a museum). Studies show that a visit to out-of-school laboratories has a positive effect on the motivational and affective characteristics of the students, but the picture is inconsistent regarding the persistence of these positive influences because the effects are short-term (Tillmann & Wenger, 2021).

Research on informal STEM activities indicates that such spaces provide opportunities for identity development that are often unavailable in formal classroom settings. These spaces allow students to pursue personal interests, develop skills in unique ways, engage with diverse cultures, involve their communities (such as family and friends), and exercise greater agency by directing their own scientific practices. This fosters empowerment and a more inclusive approach to science learning (Hazari et al. 2022).

Overall, co-curricular and informal STEM activities can contribute to students' motivational development, identity formation and agency, thereby supporting processes relevant to long-term career orientation and decision making. The Standing Conference of the Ministers of Education and Cultural Affairs (KMK) (2017) states that career education must be part of the school's curriculum and should be based on the students' interests, skills, and potential. The students should be enabled in a long-term process to make a reflected, self-responsible, cliché-free and active decision for their further education and career path.

Research Questions

Based on the theories and models presented so far, the study focuses on how students decide on their future educational pathways, particularly regarding STEM subjects and aims to answer the following questions:

1. What factors do students perceive as influential on their educational choices regarding STEM?
2. How do students develop their STEM identity (further) during grade nine and ten of schooling?
3. How do co-curricular and informal STEM activities influence students' decisions for or against STEM?

Methodology

To capture the diversity of the negotiation processes pertaining to identity development and educational pathway decisions, this study adopts an individual-centered research approach that foregrounds students' motivations and underlying meaning-making processes. Semi-structured interviews enable an in-depth reconstruction of students' self-perceptions and reasoning processes regarding STEM.

Context And Participants

To account for differences in curricula across German federal states and to reflect varied educational trajectories, students from two federal states and multiple school types are included. Except for Gymnasium students, participants are in their final two years of schooling and are facing imminent decisions about their future educational or vocational pathways; Gymnasium students may either leave after grade 10 or continue for three additional years.

Twenty-four students from six schools were selected by their teachers based on gender and STEM affinity (high/low), indicated by grades, classroom participation, and known extracurricular engagement.

Data Collection And Analysis

Data collection combines two instruments: semi-structured interviews and short written surveys. Interviews focus on students' experiences with STEM subjects, co-curricular STEM activities, informal STEM activities, the development of their STEM identities, and planned and made educational pathway decisions, while surveys capture planned educational pathways and co-curricular STEM experiences. Interviews took place in January/February and June/July of 2025 and will take place in January/February and June/July of 2026, with surveys administered in between to track changes over time and inform follow-up interviews. Due to organizational reasons, in the first interview-wave it was only twelve 9th grade students (seven female and five male) from three different schools. The interviews were transcribed using MAXQDA-Software and then manually corrected and anonymized (locations, names, etc.) in a second and third round.

The collected data is evaluated using qualitative content analysis according to Kuckartz and Rädiker (2022). A multi-stage process of category formation and coding was used. In the first coding phase the coding was carried out along the main categories that were also used in the guideline for the interviews and the STEM subjects were coded separately Within the next coding phase, the categories were developed further into the following categories: social and personal identity, significant persons, perception of STEM subjects, perceived relevance of STEM subjects, perception of STEM outside of school, STEM activities (co-curricular and informal), educational pathway decisions specified by aspired career, already chosen school subjects and career orientation. Before going into the analysis, case-specific thematic summaries were created for the individual students using the coded text passages.

In the cross-sectional analysis, the aim is to identify common patterns and themes (Kuckartz & Rädiker, 2022) based on similarities and differences between the students' narratives with respect to the aspects surveyed. These insights can contribute to sharpening the concept of STEM identity. They will also shed light on the influence of co-curricular STEM activities, informal STEM activities, especially in terms of identifying and describing key success factors.

In the planned longitudinal analysis, the changes in students' perceptions of STEM, STEM lessons and STEM identity as well as their retrospective attribution of meaning to educational pathway decisions are described. The comparison of statements on the same topic at different points in time provides information on how students are influenced by their experiences and evaluations (Rieker et al., 2024). On the one hand, the aspects described in the theoretical model are used, on the other hand it is also possible to identify new aspects and incorporate them into the model. For each student, an individual educational biography can be created and the relevant explanatory patterns for or against STEM (in the context of studies, profession, subject) can be identified.

In this article the findings of the first interviews (February 2025) will be described and discussed focusing on two students who were selected by their teachers because of their high affinity to STEM-subjects.

Findings

STEM Is Not A Unit

Before starting to go deeper into the description of the two students, it is important to note that throughout the twelve interviews the students were asked to describe and explain the term "STEM". Eight of the students didn't know the acronym while the other four said that they had heard about it but couldn't describe or explain it in detail. The interviewer gave all students a

verbal and written explanation of the acronym after the question to build a common understanding of the term STEM for the further interview.

Besides the unfamiliarity with the term STEM, what stood out within the students' answers was, that – even as the teachers who selected them were supposed to do so amongst other things by the affinity towards STEM, there was no student who liked all STEM subjects and in contrast, there also were no students who did not like all STEM subjects.

Mathematics, for example, was on the one hand characterized as easy to understand and to get good grades while time passed by fast and on the other hand the wish for a slower pace and skipping of unimportant topics were mentioned. The understanding of the content depends on the teacher's explanation. Also, students reported blackouts in tests. What stood out in comparison to other STEM subjects was that some students see their difficulties with mathematics as within themselves rather than by the lack of explanation or time. Also, the students perceived it as interesting and important for their everyday life, especially calculating e.g. the change you get in a shop and for diverse vocational fields (electrician, confectioner, insurance and banking sector).

In physics, the dislike and difficulties during class were mentioned. Besides that, it was characterized as boring and too theoretical which leads to difficulties processing the content. Special topics, e.g. electricity, gravity, and optics were described as interesting. Experiments stood out to be especially memorable. The teachers' influence on the liking of physics was rated differently. As in mathematics, the utility for the students' everyday life and their future vocation was mentioned.

Student Profiles And Influential Factors in STEM Positioning and Educational Pathways

In the following paragraphs two students (Julia and David[5]), who were interviewed in February 2025, will be described in detail regarding their positioning towards their STEM subjects, educational pathway decisions and further factors which turned out as influential for them.

"STEM Subjects [..] Run In The Family"

Julia is a 9th grade student who expresses a strong affinity for several STEM subjects, particularly mathematics, physics, chemistry, and the interdisciplinary subject 'computer science, mathematics, and physics'. Biology occupies a more neutral position in her subject preferences. She describes herself as someone who enjoys logical thinking and is able to establish connections quickly, framing these abilities as core aspects of her self-concept.

Family background plays a relevant role in Julia's positioning towards STEM. She reports that "STEM subjects in general run in the family"[6], as close family members have traditionally perceived themselves as competent especially in mathematics, even though none of them pursued a STEM-related profession. Familial recognition appears to contribute to the stabilization of her competence beliefs.

When asked about her perception of STEM, she identifies general competencies attributed to STEM professionals, including rapid comprehension, problem-solving abilities, strong intrinsic motivation, and comparatively weaker language-related skills such as vocabulary learning and memorization. Additionally, she differentiates STEM professionals' appearances across disciplines: biology and chemistry are associated with women in lab coats conducting investigations at laboratory benches, whereas mathematics was represented by a teacher carrying a brown briefcase and wearing a plaid shirt, jeans, and leather shoes.

[5] Names were selected randomly
[6] Direct quotes are translated from German to English.

Julia achieves good to very good grades in her STEM subjects and attributes her success primarily to internal factors such as logical reasoning, rapid comprehension, and sustained interest. She frequently compares her performance to that of her peers and is recognized by classmates as a source of academic support, particularly in mathematics. While this occasionally leads to social tension, it does not undermine her self-confidence; instead, it reinforces her self-positioning as competent in STEM.

Her subject choices reflect a strategic consideration of her perceived abilities, interest, and the anticipated relevance of subjects for future educational and occupational opportunities. Julia emphasizes the everyday relevance of mathematics and computer science, as well as their importance for a broader range of professional fields. Although she is uncertain about specific STEM career paths, she clearly envisions her future self within a STEM-related domain, particularly mathematics or computer science.

Co-curricular STEM activities play a comparatively minor role in Julia's narrative. She does not recall school-organized STEM activities but reports informal engagement, such as watching documentaries or visiting science exhibitions with her family. Time constraints due to multiple non-STEM hobbies limit her participation in additional STEM-related activities.

Overall, Julia's case is characterized by strong and stable competence beliefs, consistent recognition from significant others, and a future-oriented STEM-identity that extends beyond individual school subjects.

"It Just Happened"

David is also a ninth-grade student and expresses a differentiated but more ambivalent relationship with STEM subjects. He reports a strong liking of mathematics and chemistry, while physics, biology, and computer science are described as neutral. David characterizes himself as a rather quiet person when he is around people who he does not know very well and emphasizes everyday activities and social interactions outside of school.

Despite his positive experiences in some STEM subjects, David does not aspire to a STEM-related career. Instead, he envisions his future in the catering sector or in caregiving professions. These career aspirations are closely linked to professions from his family environment.

He expresses clear, stereotypical images of various STEM professionals: mathematicians are described as wearing glasses, jeans, plaid shirts, and carrying leather briefcases; computer scientists as quietly working at a computer, dressed in jeans and a pullover; natural scientists as wearing white lab coats and gloves; and technicians as performing physical labor in black shirts and work trousers.

David's competence beliefs in STEM subjects are inconsistent. While his performance in mathematics has improved over the course of his schooling and he enjoys problem solving aspects of the subject, he is unable to identify clear reasons for this development. His interest in STEM subjects is primarily topic-specific, for example related to atoms in chemistry or to gravity and electricity in physics, rather than generalized to the disciplines. Consequently, this interest does not translate into a stable STEM-related identity.

When choosing elective subjects, David explicitly decided against STEM-oriented options and in favor of AES (everyday culture, nutrition, social issues) aligning his subject choices with his occupational aspirations. He does not perceive STEM subjects as relevant for his everyday life but acknowledges their instrumental relevance for his future professions, for example mathematics for cooking (measuring ingredients) or biology for understanding the human body in caregiving contexts.

David reports no regular engagement in co-curricular or informal STEM activities. Occasional conversations about mathematics at home occur only when he finds specific topics particularly interesting. Overall, STEM does not constitute a central component of his self-concept or future imagination.

Cross-Case Comparison

Comparing Julia and David illustrates how similar levels of teacher-perceived STEM affinity can lead to fundamentally different educational aspirations. Below the authors conduct a cross-case comparison of the two students from a (STEM) identity perspective.

Competence, Performance, Recognition And Interest:

Julia expresses high competence beliefs, especially in mathematics and physics. She compares herself favourably to peers, helps others, and recognizes herself as a mathematics/STEM person. She attributes her success to internal factors such as logical thinking, quick understanding and inherent interest. Even social tension - friends "get[ting] pissed off" by her in comparison to them, high skills - does not undermine her confidence but it confirms her positioning towards STEM as competent. She chose her subjects by considering her abilities, her interest and the perceived value for her future. Her interest in STEM goes beyond school subjects as she also enjoys the STEM subjects because of their underlying logic and problem-solving nature, not just specific topics. This allows her interest to transfer across school subjects and into future aspirations. Also, she does STEM activities in her leisure time with her family and on her own but not on a regular basis.

David´s competence beliefs are more ambivalent. Although his grades improved (especially in mathematics) and he enjoys solving problems, he cannot identify the success factors for this development. He explicitly names specific topics as interesting but doesn't generalize that to the whole subject. This episodic and topic-specific (atoms, gravity, electricity) interest does not translate into sustained disciplinary identification, as once the topic changes, the interest may fade, too. He isn't involved in STEM activities but sometimes if the topic is interesting, he talks about his mathematics class. His decision against choosing a STEM subject was not due to distancing himself from STEM in general but because it does not align with how he sees himself in the future.

Comparing Julia und David illustrates how similar levels of teacher-perceived high STEM affinity can result in diverging educational aspirations. Julia's STEM identity is inter alia characterized by strong and stable competence beliefs, and consistent recognition from peers and family. This supports Hazari et al's (2010) argument that interest, competence and recognition, both self-recognition and recognition by others, are key stabilizing factors in identity development. Whereas David's STEM identity is characterized by only topic-specific interest and besides his self-recognition as a math-person he does not mention being recognized by others.

Representation Of STEM

Julia's descriptions of STEM professionals reveal some stereotypes, particularly in biology and chemistry (lab coats, working in a laboratory) and mathematics (glasses, Jeans, plaid shirt, leather briefcase) but also, she describes them as understanding things quickly, finding different ways to solve a problem and interested in their own work. A description that fits the image she draws of herself and lets her imagine to be capable of working in a STEM field.

David has also a stereotypical concept of STEM professionals (quiet computer scientist, mathematician with glasses). Even though he describes himself as quiet, he sees himself more as a cook or a caregiver. Professions which he knows from his family surroundings.

Both students' descriptions of STEM professionals reveal persistent stereotypical representations, particularly regarding appearance, work environments, and personality traits. However, these stereotypes function differently in their identity negotiation. Julia's self-description overlaps with her image of STEM professionals, enabling identification despite stereotypical imagery while David, despite partially matching some characteristics (e.g. being quiet), does not perceive STEM professions as something for him. The career he aspires is known by him due to his family members and for that it is probably more imaginable.

Educational Pathway Decisions And Future Selves

Julia imagines her future self in STEM, particularly in mathematics or computer science, even though she is uncertain about specific career paths. She is sure about her aspirations but struggles to map the field.

David imagines his future self clearly non-STEM but recognizes the need for certain topics/skills even for a non-STEM job like cook (mathematics for measuring the ingredients) or caregiver (biology to understand the human body).

Educational pathway decisions in this study appear to be strongly guided by students' future imaginaries and perceived alignment between current school subjects and envisioned adult roles. Julia's uncertainty does not concern whether she belongs in STEM, but rather how to translate her interest into concrete occupational pathways. David, on the other hand, makes a clear decision against STEM subjects not because of rejection or failure, but because STEM does not fit into his imagined future as a cook or caregiver.

Limited Salience Of Co-Curricular STEM Activities

Co-curricular STEM activities played a minor role in students' narratives at this stage. Both Julia and David struggled to recall such activities, and when they did, these experiences were not strongly linked to identity development or decision-making. This finding may reflect limited availability, insufficient integration into classroom learning, or a lack of explicit reflection opportunities. It also aligns with studies questioning the long-term impact of isolated informal STEM interventions when they are not embedded in broader educational trajectories (Tillmann & Wenger, 2021).

Discussion And Conclusion

The findings from the first interviews underline that students' decisions for or against STEM cannot be understood as binary choices, nor as a result of isolated factors. Instead, they emerge from dynamic and situated negotiation processes in which subject-specific experiences, social recognition, future imaginaries, and structural conditions interact.

A significant finding of the preliminary analysis presented in this paper is that students do not perceive STEM as a coherent or unified domain and most students were unfamiliar with the term STEM itself and even after clarification, their attitudes and identifications varied strongly across individual subjects.

David's narratives demonstrate that identification is constructed at the level of specific classroom experiences, topics, and perceived demands rather than at the level of an abstract STEM category. This differentiated positioning towards STEM subjects aligns with Hazari et al.'s (2010) emphasis on subject-specific identity components such as interest, competence beliefs or recognition. On the contrary Julia's narratives demonstrate that she sees her current and future self as a STEM person linking this self-description to a more abstract level of STEM categories like quick understanding and logical thinking.

The study contributes to STEM identity research by empirically illustrating how similarly perceived high STEM affinity can lead to divergent trajectories and by highlighting the importance of reflexive sense-making in identity stabilization. Methodologically, the longitudinal approach holds promise for capturing how critical moments, experiences, and interpretations accumulate over time.

However, the findings are based on a limited, selective number of interviews and should therefore be interpreted cautiously. Future analyses will benefit from the full longitudinal dataset, allowing for a more nuanced understanding of negotiation processes and probably the delayed impact of co-curricular and informal STEM experiences.

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Queer In STEM Queering STEM: The Story And Insights Of A Trans, Ace, White Woman In Chemical Engineering

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*This case study explores the intersections of trans*ness and STEM through a combined framework of queer theory, intersectionality, the construct of figured worlds and science identity. The study uses a life-history approach to characterize the trajectory of Cassandra, a trans, ace, white woman in Chemical Engineering. We collected data through in-depth, semi-structured interviews which we analysed in three rounds using narrative analysis, artefacts, such as the River of Life, and a focus group consisted of queer and trans individuals, including Cassandra, to identify aspects of STEM education that constrained or supported the participants' trajectory and to offer strategies for queering STEM educational spaces. The findings of this study include data of the participant's reflections on her STEM trajectory as for example, the course of her life as she moved towards or away from STEM. Moreover, the findings illustrate the exclusionary cultural models of the figured world of STEM, that were shaped by cisheteronormativity, sexism, white supremacy, ableism, defined by neoliberal values and depoliticized. Finally, the findings highlight the importance of transforming a) the culture of STEM, b) the image of STEM, c) the curriculum and pedagogies, and d) the teacher-student relationships, to foster more inclusive and affirming environments. The study aims to challenge cisheteronormative frameworks, promoting a reimagined and supportive learning environment for all students.*

Keywords: Gender equity, Inclusive Education, Science Identities

Introduction

Broadening STEM participation is a central focus within the STEM education community. Research indicates that enduring inequalities in STEM perpetuate the dominance of white males, while women, people of colour, and individuals with disabilities face underrepresentation (NSF, 2021). Queer individuals have also been recognized as an underserved group. Despite limited data, studies reveal that queer individuals face exclusion, discrimination, and harassment in STEM, which affects their careers, prompting the need to examine both the mechanisms that marginalize them and the factors that sustain their persistence, and leading to a push to reimagine academic environments and transform STEM education spaces (Marosi, 2024). Addressing inequalities in STEM is essential for reducing disparities and fostering inclusive, sustainable development (UNESCO, 2024).

Therefore, this study aims to contribute to the queering of STEM by a) exploring the intersections of trans*ness with the science identity throughout schooling and university, and by b) using a bottom-up approach, prioritizing the voices of marginalized individuals in the process of transforming STEM education. This study is part of a larger project for which we conducted interviews and a focus group with queer individuals, but we currently present the findings relevant to Cassandra, a trans woman in Chemical Engineering. The research questions were the following:

- How did the participant (re)negotiate her science identity throughout her educational trajectory?
- How do the intersections of her social identities shape and interact with the cultural norms of the figured world of science to afford or constrain her participation?

- How does she envision queering science education based on her lived experience?

Theoretical Framework

This study combines queer theory and intersectionality to analyse how power, privilege, and oppression shape the lives of the participant in STEM, using the constructs of figured worlds and science identity to explore her positioning in and out of STEM spaces. Queer theory challenges normative binaries of gender (Gunkel 2009), while intersectionality examines the interconnected forms of oppression that shape identity and lived experiences (Crenshaw, 1989). Science identity, a construct tied to how individuals see themselves and are recognized as science participants, highlights the role of recognition and co-construction in fostering engagement and persistence in science (Carlone & Johnson, 2007). Figured worlds frame these identities by establishing cultural models and norms that determine who is valued and recognized within the STEM community, with these models influenced by broader societal structures and localized contexts (Gonsalves, 2014). Together, these frameworks provide a lens to explore how cultural norms in STEM afford or constrain Cassandra's participation and identity development.

Method

We employed a qualitative case study approach. We utilized artefacts (River of Life, a visual exercise that helped participants to map out their science trajectory) and semi-structured interviews which we analysed in three rounds using narrative analysis, to explore participants' STEM trajectories, focusing on the intersections of queerness and STEM. After the interviews, we developed conceptual themes addressing problematic aspects of STEM education and participants' suggestions for queering these areas. An online focus group was then conducted to collaboratively generate ideas for queer-affirmative STEM education from a bottom-up perspective. The participants were purposefully selected from social media. The current study presents the findings relevant to Cassandra, a 27-year-old, trans, lesbian, ace, white woman who grew up and studied in the US and is currently a lecturer in Chemical Engineering in the US.

For the purpose of data analysis, we transcribed the interviews and focus group discussions verbatim and analysed them using Atlas software. Through in vivo and line-by-line coding, we prioritized the participant's direct statements while minimizing researcher interpretation. An inductive and deductive approach was used to identify: a) elements or experiences limiting identification and participation in STEM, and b) ways to queer STEM education. Trustworthiness was ensured through triangulation, verbatim transcripts with in vivo coding to reflect participants' voices, and member checking to validate interpretations with the participants.

Findings

Cassandra's Story

Cassandra, who grew up in a privileged, conservative, all-white town in the US and was perceived as a cis-heterosexual male before transitioning during grad school, was deliberately pushed into STEM from an early age, benefiting from systemic privilege and familial support, which shaped her STEM trajectory despite her awareness of the sexism, elitism, and competitiveness in engineering spaces. Cassandra's experience in engineering was marked by an elitist and competitive culture that promoted the idea of exceptional individual labor while marginalizing certain identities, such as neurodivergent, queer, and trans individuals. Faculty and institutional norms supported exclusionary practices, with high dropout rates and strict expectations for "good students" that had a bigger impact on marginalized groups. Bioessentialism and the lack of queer representation further alienated individuals, as gender and queer issues were largely absent from

STEM spaces, leaving students like Cassandra without visible role models or safe opportunities for expression.

Cassandra's pre-transition years were marked by dissociation and intense academic focus, using her demanding engineering studies as a way to avoid confronting her gender identity. After transitioning, with the crucial support of friends, the queer community, and supportive women in her faculty, she began to feel more aligned with her true self, discovering a passion for teaching engineering that gave her life new meaning despite initial challenges. Cassandra's transition allowed her to live authentically and brought a holistic connection between her mind and body, making her a happier and more empathetic person. Now a lecturer in Chemical Engineering and an advocate for inclusive education, she integrates her lived experiences into her teaching and activism, challenging patriarchal and exclusionary norms in STEM and creating spaces where everyone can bring their full selves into STEM.

Envisioning A Queer Inclusive STEM Education

This section highlights various problematic aspects of science education which hindered participants' progress in science as highlighted by the participants in the interviews and the focus group, namely the a) culture of STEM, b) image of STEM, c) curriculum and pedagogies, and d) relationships and presents their strategies for queering these aspects. In what follows, we present the findings relevant to Cassandra. According to Cassandra, the culture of STEM often reinforces cisheteronormativity, sexism, and bioessentialism, marginalizing queer individuals and perpetuating harmful stereotypes. As Cassandra stated, besides implementing policies that protect queer individuals, "What you shouldn't do is attach our gendered expectations to like cells and molecules and atoms and animals as well [...] maybe we shouldn't assign any agency or passivity to fucking animals," emphasizing the need to challenge gendered biases and adopt inclusive, curiosity-driven perspectives for more accurate scientific inquiry.

The competitive, individualistic, and elitist culture in science often stifles collaboration, fosters harmful competition, and negatively impacts mental health and inclusivity, with Cassandra critiquing this mindset, saying, "I don't want to win so that someone else loses [...] I want us all to win. I want to collaborate." She actively works to counter these norms by abolishing exams in her classroom, implementing labour-based grading, promoting collaboration, and advocating for sharing both successes and failures in scientific research to improve transparency and inclusivity.

Cassandra critiqued the traditional image of scientists as white, middle-class, cisgender, straight men, highlighting the lack of representation of queer and trans identities and the depoliticized portrayal of STEM disconnected from social issues. Cassandra proposed queering this image by integrating social justice into STEM education, emphasizing diverse contributions, promoting authentic self-expression, and redefining success to prioritize mental health, community, and diverse career paths over financial gain or traditional metrics of achievement: "You don't have to be the guy and I do mean guy in this case, who makes 100k," and questioning "What is the point of diversity in STEM? Are we going to try to make more Black Raytheon employees, more female oil drillers, more non-binary forest destroyers?"

She also criticized the absence of queer issues in STEM curricula, highlighting the need to challenge Western science's claim to pure objectivity, advocating for the inclusion of diverse epistemologies, including feminist, Indigenous, and queer perspectives, to reshape both the curriculum and pedagogy. She emphasized the importance of integrating social justice and mental health into teaching, suggesting that STEM education should be more inclusive and adaptable, while also advocating for a rebalancing of tenure criteria to prioritize teaching alongside research: "How do we rebalance that and make it so that teaching is weighted more in the tenure process?"

Finally, Cassandra emphasized the importance of personal relationships in STEM, noting that a supportive faculty member helped her maintain mental stability when she was struggling with her trans identity: "It was because of her, that I didn't completely lose my mind." She also stressed the need to challenge hierarchies in the classroom, advocating for a more empathetic, care-driven approach to teaching that includes affirming students' identities, offering mental health resources, and creating inclusive environments. An example of her behaviour is when she opened one of her classes with a big slide saying: I give a shit about you", underlining her commitment to her students' well-being.

Discussion

In response to the first research question, the cultural models of STEM in the story of Cassandra often reinforced exclusionary norms, portraying fields like engineering as competitive, masculine, and elitist, while marginalizing queer and trans identities and individuals with mental health challenges. This created environments that prioritized individual achievement over collective support and depoliticized social issues. Addressing the second research question, Cassandra's identity trajectory in STEM was shaped by her initial alignment with privileged cultural models as a cisgender, able-bodied, white, middle-class person. However, after transitioning during her PhD, she faced the challenges of navigating a still-exclusionary field. With the support of others, she embraced her transness, which ultimately reshaped her path towards a more inclusive and socially conscious role in academia.

Finally, in response to the third research question, Cassandra emphasized the need to address heteronormativity and sexism in STEM by implementing policies that protect marginalized groups and challenge gendered language and biases. She pointed out that neoliberal and competitive structures in STEM promote individualism and elitism, which hinder collaboration and innovation, and called for education reforms such as labor-based grading contracts and a greater focus on interdisciplinary work. Additionally, she argued that true diversity in STEM requires more than superficial representation; it necessitates a shift toward inclusive perspectives, alternative career paths, and the dismantling of traditional norms and capitalist-driven roles. Recognizing the depoliticized nature of STEM education, she advocated for queering the field to reintroduce discussions on power, social justice, and exploitation, while challenging capitalist and gender norms. Furthermore, she emphasized the importance of dismantling hierarchical structures in classrooms by fostering personal, empathetic teacher-student relationships that promote inclusivity, respect, and safety, particularly for marginalized groups.

Implications

This study emphasizes the marginalization of trans individuals in STEM and calls for the redesign of learning spaces, the exploration of intersectional identities, and the implementation of inclusive policies, support networks, and queer-inclusive pedagogies to foster diversity and inclusion. It also suggests further research on integrating critical theories, inclusive curricula, and alternative assessments to address systemic barriers.

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A Multiple Case Study Of Translanguaging And Systemic Functional Linguistics In K-12 Science Education

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This multiple case study explores how science teachers interact with and respond to translanguaging as it naturally occurs among English Learners (ELs) who bring varied levels of English proficiency into distinct classroom contexts. The study focuses on two participants working in linguistically diverse public schools: one 6th grade biology teacher who is monolingual English-speaking and identifies as White/Caucasian, and one 10th grade chemistry teacher who identifies as Hispanic/Latine and is bilingual in English and Spanish. Using a Systemic Functional Linguistic (SFL) framework as a lens, we examine how translanguaging manifests within the three metafunctions of language: ideational, interpersonal, and textual. Classroom data included audio and video recordings of both teachers and students (n = 88) during routine science instruction to analyse when and where translanguaging occurred, to whom it was directed towards, and how instructional tasks created space for its use. Semi-structured interviews offered further insight into how teachers understood and navigated linguistic diversity in their classrooms. Findings suggest that translanguaging emerges through fluid, collaborative classroom discourse and is shaped by teachers' language-related decisions, including how they (1) use language to scaffold scientific reasoning, (2) attend to the functional purposes of language in content learning, and (3) affirm bi/multilingual expression as a resource for students' meaning-making in science classrooms.

Keywords: Classroom Practices, Languages and literacies in science education, Multicultural Education

Introduction

In the United States (U.S.), schools test multilingual students upon entry to determine whether they need language support to succeed. If they do, they are classified as English Learners (ELs). ELs in U.S. science classrooms face the dual task of understanding scientific content while simultaneously developing English proficiency (Garza & Arreguín-Anderson, 2018; Meskill & Oliviera, 2019). This cognitive and linguistic demand can hinder their ability to fully engage in ambitious science learning practices, which require reasoning, argumentation, and evidence-based explanations (Windschitl et al., 2020). Translanguaging, a pedagogical approach that encourages students to use their entire linguistic background to inform meaning-making processes, has emerged as a promising strategy to address this gap in learning environments (García & Lin, 2016; Wei, 2018). However, little is known about how varying instructional practices either encourage or impede translanguaging in science classrooms.

To address this gap, systemic functional linguistics (SFL) provides a valuable critical lens for understanding how teachers use or encourage translanguaging to guide ELs through scientific reasoning and discourse. SFL views language as a semiotic tool for meaning-making and emphasizes the importance of helping students navigate the linguistic features (e.g., terminology) of academic disciplines, such as science (Schleppegrell & Oteíza, 2024; García & Kleyn, 2016). Central to SFL are the three semantic metafunctions: (1) the ideational, which focuses on how language represents and organizes experiences and knowledge; (2) the interpersonal, which examines how language facilitates social interactions and expresses attitudes and relationships;

and (3) the textual, which explores how language creates cohesive and meaningful communication (Banks, 2002). We position SFL as a theoretical framework to analyse how teachers and students use language in the classroom. Through this framework, we examine how teachers and students leverage their linguistic backgrounds to connect prior knowledge to new scientific concepts (ideational), engage in argumentation through collaborative learning (interpersonal), and organize thoughts cohesively to communicate scientific ideas (textual). By investigating teachers' pedagogical strategies, we aim to understand teachers' (1) purposes for language use in science classrooms and (2) how they legitimize translanguaging as a linguistic tool for meaning-making. Therefore, we are motivated by the following research question: *How do science teachers create opportunities for translanguaging in their varied learning environments to support English Learners in science classrooms?*

Methods

Participant Selection

Participants included two science teachers from different U.S. school districts in the Midwest: 1) Aaron, a 6th-grade biology teacher in a small rural city with a monolingual English background, and 2) Maria, a 10th-grade chemistry teacher in a suburban Midwestern city, who grew up as a dual-language student, speaking both English and Spanish. They were selected due to their experience teaching science and simultaneously teaching ELs and monolingual English speakers in the same classroom. Both teachers worked with ELs from different linguistic backgrounds, including Spanish and Arabic, at varying levels of English proficiency. Student participants included 64 students from Aaron's biology classes and 22 from Maria's chemistry class (N = 88).

Data Collection

We employed semi-structured interview and observation protocols (Authors, 2013), including audio and video recordings of teachers' science classes. In the first stage (individual interviews), we met virtually with Aaron and Maria to discuss their teaching background, views on language use in their schools, and their students' linguistic and learning environments. Sample interview questions included: "How do your students translanguage (fluidly switch between English and Spanish or other languages) during learning?" "When and where does this likely occur?" and "Why do you feel that your students do this?" Additionally, we asked, "How do you encourage and/or scaffold translanguaging practices during instruction?" In the second stage (classroom observations), we observed 10 classroom periods over the span of four days. To highlight pedagogical strategies and language use, we used 8 hours of video and audio from both classroom observations and individual interviews.

Data Analysis

We employed a multiple case study design (Román, 2013) to examine science teachers' perspectives on working with ELs and the factors influencing their translanguaging practices. This method let us capture individual differences and shared approaches in how teachers used translanguaging strategies to support ELs during science instruction. Applying an SFL lens, we used a priori codes derived from the ideational, interpersonal, and textual metafunctions of language to code the notes from observations and interview transcriptions. This allowed us to investigate how teachers' translanguaging practices support meaning-making, social interaction, and coherence in science classrooms.

Results

Ideational: Connecting The Language Of Science To Real-World Contexts

Aaron led a project where students designed reusable cups using recyclable materials and tested how well they maintained drink temperatures as a way to examine thermal energy transfer. He tapped into the ideational metafunction of language by connecting the concept of thermal energy transfer to his students' real-world experiences. For instance, Aaron problematized the design challenge by explaining how iced drinks from coffee shops often warm up too quickly on sunny days, prompting students to think critically about an innovative design solution. ELs in Aaron's class used translanguaging to connect this knowledge to the scientific concept of energy transfer. For example, three students, Nora, Ryan, and Maya, discussed using aluminum foil to contain more heat inside the bottom of their cup (see Figure 1).

Figure 1. Transcript on English Learners' Interactions Representing the Ideational Metafunction.

Nora: *Oh Ryan, you gave me an idea. When I make this thing, right? [points to the fabric intended for the bottom of the cup] we put the aluminum in the bottom.*
Ryan: *Mucho? A lot?*
Nora: *Maybe, yeah maybe.*
Ryan: *Alright, but we are not gonna use this [points to fabric] in the bottom.*
Nora: *No, like. Porque mira, dame eso [Ryan hands Nora the fabric]... okay so it's gonna be like this right? [shows the fabric material] And we put alumino aqui right? [points to the inside of the fabric]. I don't know.*
Ryan: *Mmm I don't think so.*
Maya: *I don't know.*
[All students think for a moment]
Ryan: *I don't think that will work ... probably actually .. yeah it probably would, yeah*
Nora: *Pick, pick right now. Yes or no? Are you sure?*
Ryan: *Yes.*
Nora: *Positive? Seguro? Si?*
Ryan: *Yes, yes, yes*

In the figure above, Ryan invites translanguaging into meaning-making when he uses "Mucho?" followed by the English version of the question, "A lot?" This shows students all language varieties are welcomed. Nora then uses Spanish later on, "Porque mira, dame eso," to ask Ryan to hand her the fabric while continuing to make sense of the phenomenon without worrying about *what language* counts as the language of science.

Similarly to Aaron, Maria's teaching focused on reducing cognitive load and making scientific concepts accessible to her ELs. In her 10th-grade chemistry unit on the electronegativity of atoms, she used Spanish to support her ELs, explaining, *"My expectation for them is to try and write in English, but that doesn't necessarily happen because they can't really express themselves very well in English. We teach all the vocabulary in English, so I expect them to use those words… but I allow them to produce in their home language using a Chromebook to translate."* By providing key vocabulary in English while allowing students to produce work in their home languages, Maria helped students construct scientific meaning while navigating English as an additional language.

Interpersonal: Building Collaborative Translanguaging Spaces

Despite being a monolingual English speaker, Aaron created opportunities for interpersonal interactions by intentionally pairing students with varying levels of English proficiency in small groups during classroom instruction (e.g., students with higher English proficiency worked with students with lower English skills). We noticed that ELs with varying levels of English proficiency spoke predominantly in Spanish when forming the majority in their small groups, particularly after being prompted by the research team to use whatever language they feel comfortable with. On day two of our observations, Aaron reflected on this, stating, *"I had never heard them [group of ELs] speaking Spanish before this. It's great."* Although Aaron did not explicitly encourage his students to use their home language, his receptiveness to ELs' translanguaging practices highlights his adaptability to foster a classroom environment that embraces linguistic diversity.

In contrast to Aaron's pedagogical strategies, Maria fostered an inclusive environment by leveraging her bilingualism to support her ELs. Early in the school year, she paired students who spoke the same language (e.g., Spanish-speaking students and Arabic-speaking students) to encourage dialogue, while gradually transitioning them to work with monolingual peers to promote English use. Reflecting on the dynamics in her classroom, she said, *"It's frustrating for me because I try to only speak in English to them, but since they know I speak Spanish, their comfort level in Spanish is way higher in my classroom."* While she aimed to speak only in English, Maria recognized that her bilingualism increased students' comfort, especially for those with lower English proficiency who might otherwise avoid engaging.

Textual: Supporting Meaningful Language Use Through Structured Scaffolding

Aaron's use of scaffolding strategies helped his ELs navigate the task of learning science content in their non-native language. For instance, he adjusted expectations for language use depending on the task, stating, *"I have students just write in Spanish if the task is a 'heavier lift' in my class. Final assessments can be completed in Spanish so that students engage more deeply with the content rather than focusing on the language …"* By focusing on how students' linguistic and cultural resources could be leveraged in meaning-making, Aaron enabled students to draw from both their home languages and English to structure their scientific ideas cohesively.

Unlike Aaron, who supported translanguaging between ELs, Maria led a discussion with two ELs about how atoms with higher electronegativity "steal" electrons from other atoms when forming bonds. Following the textual metafunction, Maria used translanguaging as a pedagogical strategy to help Carmela, one of the native Spanish-speaking ELs, articulate her understanding (See Figure 2).

Figure 2. Transcript on Teacher-Student Interaction Representing the Textual Metafunction.

Maria: *Okay so let's talk. So the other one ... [points to atom] everything around it was the same, right?*
Carmela: *Mhmm.*
Maria: *It was chlorine, chlorine, chlorine, chlorine [points]. What do you notice about this one? What do you guys think? [points at two Spanish-speaking students]*
Carmela: *This is named, es hidrógeno, es el primero, no?.... Electrones ...*
Maria: *Right, and we have a different atom here than chlorine, and you see how it's partially positive. On the other one, everything was partially negative ... What's the electronegativity of carbon?*
Carmela: *¿Qué?*
Maria: *¿Qué es la electronegatividad de carbón?*
Carmela: *Ahhh, yo sé son los electrones*
Maria: *2.5, right? And what's the electronegativity of chlorine? So who's gonna steal the electrons?*
Carmela: *Como ellos son los fuertes, ¿le roban a este?*
Maria: *Ahaa, so it's gonna pull a little bit, right?*
Carmela: *Mhm. Ohhhh.*
Maria: *And here we're stealing the electrons. So electrons move this way.*
Carmela: *Ohhhh. Entonces este le quita a este y estos le quitan a este?... "*

In the above interaction, Maria's prompting guided Carmela to connect her prior knowledge to understand electronegativity. When Carmela initially didn't understand the question in English, Maria clarified it in Spanish: "¿Qué es la electronegatividad de carbón?" This allowed Carmela to recall relevant information and respond, "Ahhh, yo sé son los electrones." As the conversation progressed, Carmela used her linguistic background to reason in Spanish. Through a textual lens, Maria demonstrated how translanguaging helped Carmela organize and communicate complex scientific ideas while drawing on her native language and the language of instruction. Unlike a traditional approach, where students in science classrooms construct their reasoning in a single language (e.g., English), Maria allowed Carmela to use her full linguistic background to structure her questions and responses across languages.

Discussion

By situating translanguaging within an SFL framework, this study highlights the interconnected roles of ideational, interpersonal, and textual metafunctions in shaping how language supports science learning. As translanguaging continues to gain recognition as a legitimate pedagogical tool, science educators are encouraged to embrace linguistically responsive teaching practices that empower ELs to participate fully in rigorous scientific inquiry.

Case studies revealed that translanguaging practices are implemented according to science teachers' pedagogical strategies and the teachers' and students' linguistic backgrounds. While Aaron encouraged translanguaging by enabling collaborative group work between students with similar multilingual backgrounds, Maria engaged her ELs in both English and Spanish to support their scientific reasoning. Both teachers demonstrated that, when purposefully integrated, translanguaging can promote conceptual understanding, reduce cognitive load, and create more inclusive science learning environments.

Future research can examine how institutional factors, such as school language policies and curriculum design, further influence teachers' ability to adopt translanguaging practices. Additionally, future studies can analyse content teachers' translanguaging practices across academic subjects (e.g., social studies, mathematics, and language arts).

Ultimately, embracing translanguaging as a pedagogical tool, whether teachers are bilingual or monolingual, can help educational researchers, teachers, and school networks reframe multilingualism as an asset. It fosters more equitable and engaging learning environments for ELs in science classrooms and beyond.

Acknowledgement

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Exploring STEM Identity Development In Early Science Education In Germany: Gender Differences And The Impact Of Science Capital

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Despite the acknowledged societal relevance of physics, many students distance themselves from the subject, perceiving it as both challenging and male dominated. Such perceptions contribute to smaller, less diverse scientific communities. To better understand science-related educational decisions, this study applies the STEM identity framework in a longitudinal design, integrating qualitative and quantitative methods. The focus is on the early stages of physics and chemistry education at the age of 12-15 years. The longitudinal questionnaire survey presented here, was conducted at 15 German grammar schools with 688 students over two years, using validated scales to assess identity related constructs like self-efficacy and interest. Results show gender disparities in interest and self-efficacy at the beginning of physics and chemistry lessons, with males reporting higher levels. Regarding Science Capital we found that students with higher Science Capital display higher levels of interest and self-efficacy. The gap between the groups became smaller during the observation period, but at the same time self-efficacy and interest in the subjects generally declined, with the exception of biology. However, the downward trend is more pronounced among male students and students with higher Science Capital. These findings highlight the role of gender and Science Capital in shaping early STEM experiences, with problematic trends particularly evident in physics-related constructs.

Keywords: Early Science Education, Longitudinal Studies, Science Identities

Theoretical Framework And Research Interest

Although the social relevance of the natural sciences in general and physics in particular is recognised by a large number of people, many pupils personally distance themselves from physics (Archer et al., 2010). Physics is often regarded as a difficult, nerdy, male and unpopular school subject (Kessels et al., 2006). Accordingly, educational decisions are often made against physics which, among other things, leads to fewer and less diverse young scientists (DeWitt & Archer, 2015).

The construct of identity affords a comprehensive framework for examining educational choices, conceptualizing them as emergent from intrapersonal negotiations (identity work) embedded within an individual's social environment. It allows a wide range of influences and underlying conditions to be taken into account (Lee, 2012; Morf & Koole, 2014). This theoretical premise suggests to integrate qualitative approaches (via narratives, e.g. from interviews) and quantitative approaches (e.g. via psychological constructs from questionnaires). Psychological constructs such as self-efficacy, interest and self-concept in science can be taken as indicators of a comprehensive STEM identity (Hazari et al., 2010; Rabe & Krey, 2018).

With regard to science education, the initial subject classes can be considered a critical phase in students' educational decision-making. In German grammar schools these begin in the 6th or 7th grade and coincide with the onset of adolescence, when identities are strongly (re)negotiated (Schreiner & Sjøberg, 2007). Analysing this phase from the perspective of STEM identity is still a desideratum in Germany (Rabe & Krey, 2018).

Research Questions And Methods

Our research project aims to use the identity perspective to better understand young people's educational decisions and, in particular, to shed light on the identity negotiations in initial physics and chemistry classes. To this end, we focus on the research questions: (1) How do indicators of a STEM identity develop in introductory physics and chemistry classes? (2) How do students relate other identities (e.g. gender) to their developing STEM identity?

To answer the research questions, the project IdentMINT uses a mixed methods approach with qualitative interviews and a quantitative longitudinal questionnaire survey. In the following, we report on the quantitative part of the inquiry.

Surveys were carried out in two federal states of Germany at a total of 15 grammar schools (9 in Bavaria and 6 in Saxony-Anhalt) at three points in time (T1-T3). The surveys cover a period of nearly two years of initial physics (T1-T3) and one year of chemistry (T2-T3) classes. Complete data sets covering all survey points are available for n=688 pupils, 56% of whom identify as female, 43% male, 0.7% diverse or unspecified.

We used established scales to gather data on identity related constructs, including self-efficacy related to physics, chemistry, and biology (Jerusalem & Satow, 1999), interest in physics and chemistry (Frey et al., 2009), perceptions of physics and chemistry lessons, engagement in extracurricular science activities, aspects of gender identity, Science Capital and the perceived attitudes of significant others, such as peers and parents (ASPIRES, 2016). In the following, we report on the constructs of interest and self-efficacy. These scales have undergone validation through confirmatory factor analysis (Hu & Bentler, 1999) and have been tested for measurement invariance (Chen, 2007), which is essential for our cross-sectional and longitudinal analyses. With the validated scales, we conducted cross-sectional mean comparisons (Wilcox tests due to robustness against violation of normal distribution) with comparisons by gender and by the parents' occupational background in natural sciences as an indicator of Science Capital. We distinguished between students having none, one or two parent(s) with an occupational background in science. Effect sizes are reported using Cohen’s d. For the longitudinal analysis, we performed an ANOVA for repeated measurement and then conducted paired Wilcoxon tests between T1-T3 and calculated effect sizes of the longitudinal development.

Results: Development Of Self-Efficacy And Interest

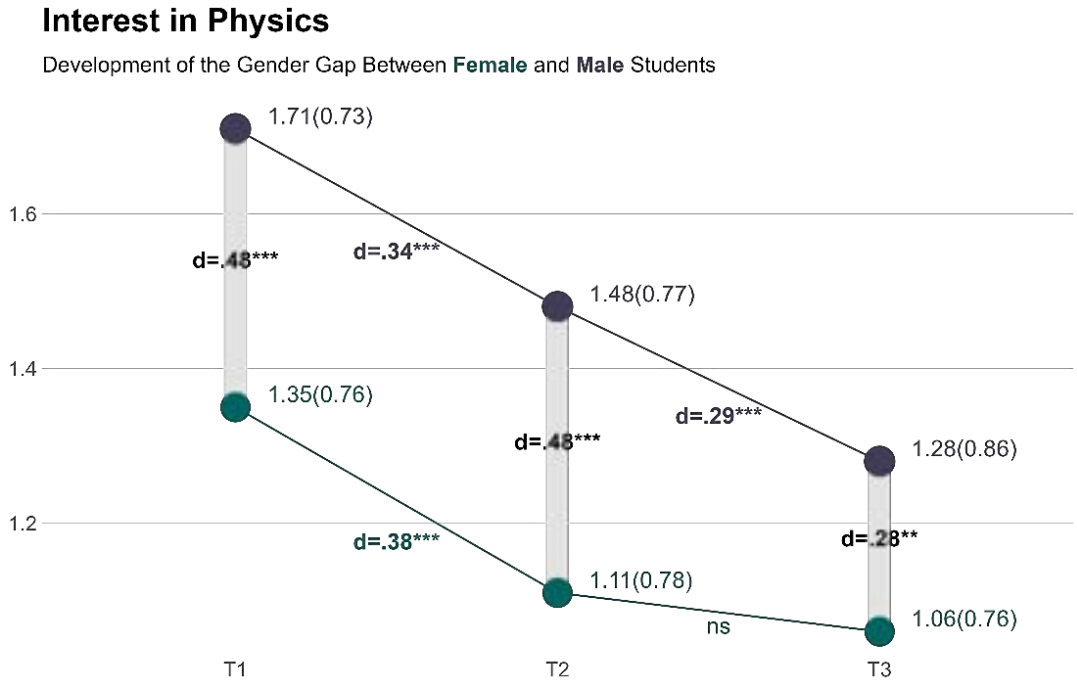
All scales show a satisfactory quality according to Hu & Bentler (1999). Cross sectional measurement invariance with the criterion according to Chen (2007) is given for almost all group comparisons with $\Delta CFI<.01$ (if not, no differences are reported or explicit reference is made to the violation of measurement invariance). Longitudinal measurement invariance across the survey time is given (with $\Delta CFI<.01$) in all groups except for the group with two parents with a background in natural sciences. In the following, we present the developments of self-efficacy in physics, chemistry and biology, as well as interest in physics and chemistry.

Gender Specific Results

Due to the small number of participants who identify as diverse, the gender specific results are only given for male and female students. The results for biology differ significantly from the other two natural sciences: There are no significant gender differences for self-efficacy in biology at T1 and T2 (with no measurement invariance at T3). In physics and chemistry, we find a significant and substantial gap in interest and self-efficacy, with male pupils reporting higher scores at the beginning of the initial lessons. The largest gender gap is found for self-efficacy in physics (d=.62*** at T1) and for interest in physics (d=.48*** at T1 and T2). All observed gender

gaps are smaller at the end of the two-year survey period and are only significant for physics-related constructs. For self-efficacy in physics, the gender effect decreases from medium (d=.62***) to small (d=.38**), and similarly for interest in physics from d=.48*** to d=.28** (see Figure 1). The gender differences in chemistry decrease from d=.33*** to d=.10 for self-efficacy and from d=.28*** to d=.06 for interest and are no longer significant at the end of the survey period. This observation is mainly due to the fact that most of the values decrease in both groups (there is only one slightly significant but very small increase in self-efficacy in biology from T2 to T3: d=.17** all other values decrease or remain unchanged). However, the longitudinal decline is much larger for male students than for female students (e.g. from T1 to T3 for interest in physics for female students with d=.38*** and for male students with d=.54***). The development of the effect sizes of the group differences between female and male pupils is summarised in Figure 4 on the left.

Figure 1. Development of the gender gap in interest in physics (scale 0 to 3) over the three survey points (T1 to T3); for cross sectional and longitudinal effects Cohens' d is shown.



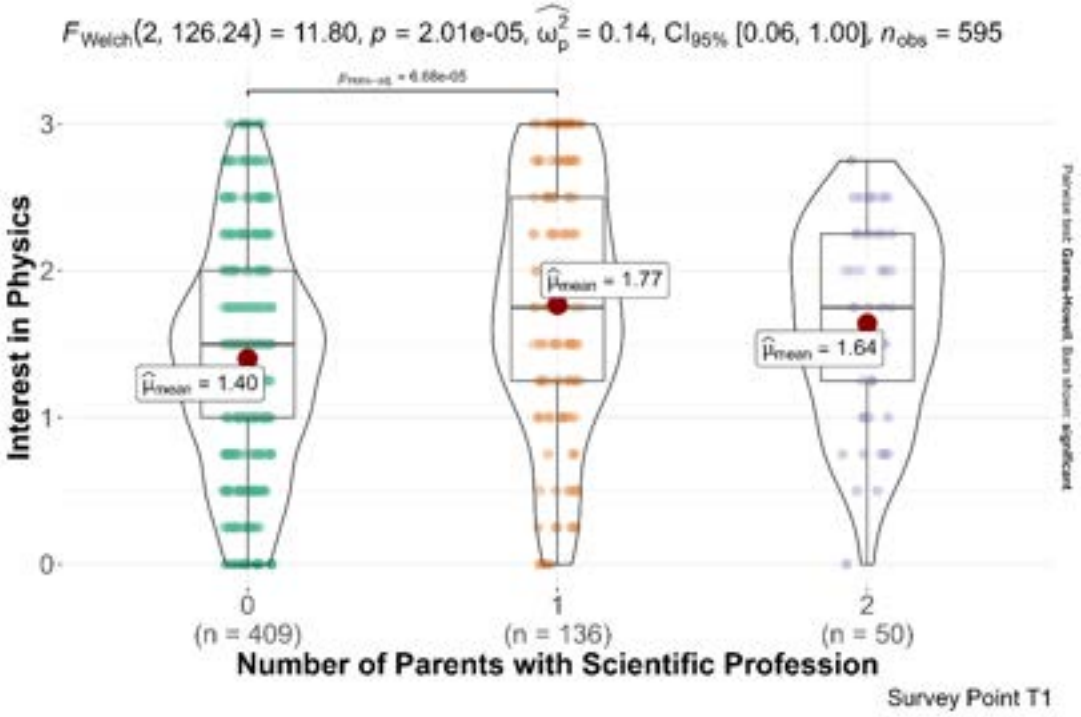
Results On Science Capital

As a means of accessing Science Capital, we examined the professional background of the parents. Participants were asked whether their parents have a job related to science. It is important to note that the survey measured pupils' perceptions of whether their parents' occupations were related to science – rather than an 'objective' classification of specific jobs. From this, we formed groups of pupils without a science-related parent (n=458), pupils with one parent with a science-related background (n=156) and pupils who stated that both parents have a science-related occupation (n=53). In 21 cases, there were no responses or invalid responses. We then analysed whether there are significant differences in self-efficacy and interest and how the constructs develop in the three subgroups over the study period.

In the first survey (T1 for the physics and biology related variables, T2 for chemistry related variables), there are significant differences with medium effect sizes (d>.25*) in all reported variables between the group with one and the group without parents with a scientific occupation.

Students with a science background report higher levels of interest and self-efficacy at all data collection points. The largest differences due to Science Capital can be observed in interest in physics (d=.46*** at T1) and interest in chemistry (d=.39*** at T2). Surprisingly, there are no significantly higher values in the group with two parents working in science-related professions; in fact, for some measures, such as interest in physics the mean values are even lower in this group (see Figure 2).

Figure 2. Interest in physics at survey point T1 showing higher values for students with one parent working in a science-related profession, but no higher values, if both parents have a background in natural sciences.

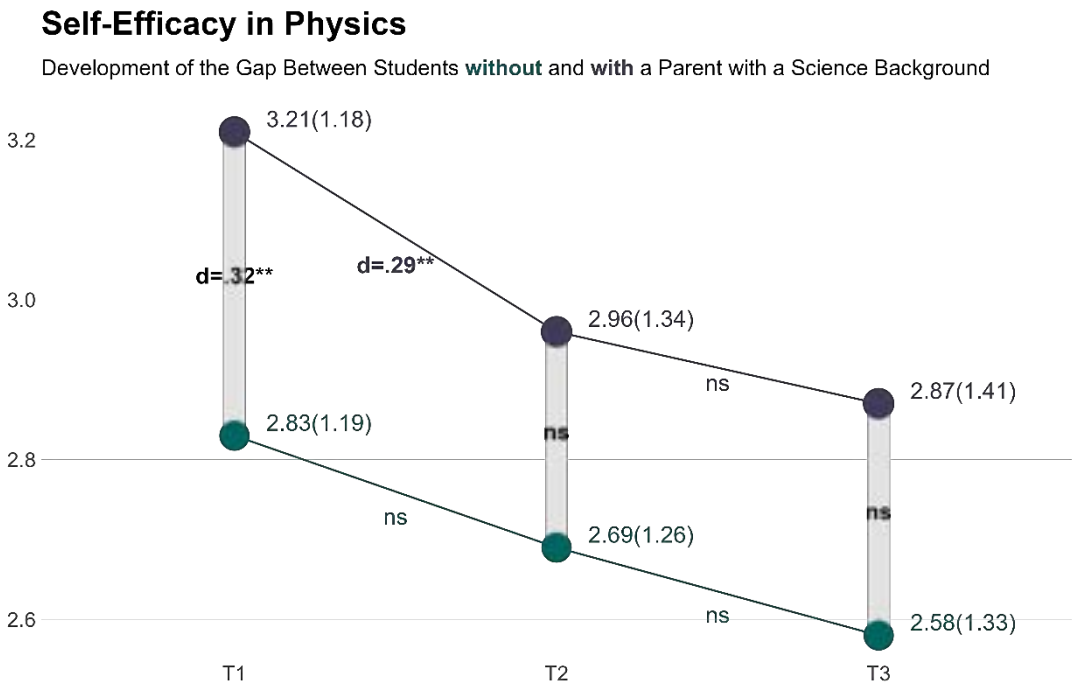


Due to a lack of longitudinal measurement invariance for the group with two parents with scientific professions, the development of interest and self-efficacy is only reported for the other two groups (without and with one parent with a scientific profession).

In contrast to the gender gap, we found a gap in self-efficacy expectations in biology depending on Science Capital (d=.25* at T1 and d=.27* at T2). Almost no significant longitudinal developments can be observed for the self-efficacy in biology. In the group without a parent with a scientific background, self-efficacy in biology increases slightly from T2 to T3 (d=.12*), so that the Science Capital gap at T3 is no longer significant (d=.18).

For interest and self-efficacy in physics and chemistry, we see – similar to the gender gap – that high values (in the groups with high Science Capital) decline the most over the survey period. For example, the decrease in self-efficacy in chemistry is much lower for the group without scientific parents (d=.15**) than in the group with one parent with a science background (d=.35**) from T2 to T3. Due to these longitudinal trends, the differences between the Science Capital groups become smaller and, at the last survey point, are only measurable in terms of interest in physics (d=.40***) and chemistry (d=.27*). All group differences regarding self-efficacy are no longer significant at T3 (see Figure 3 for self-efficacy in physics and Figure 4 for all reported scales).

Figure 3. Development of the Science Capital gap in self-efficacy in physics (scale 0 to 5); Cohen's d is provided for cross sectional and longitudinal effects.

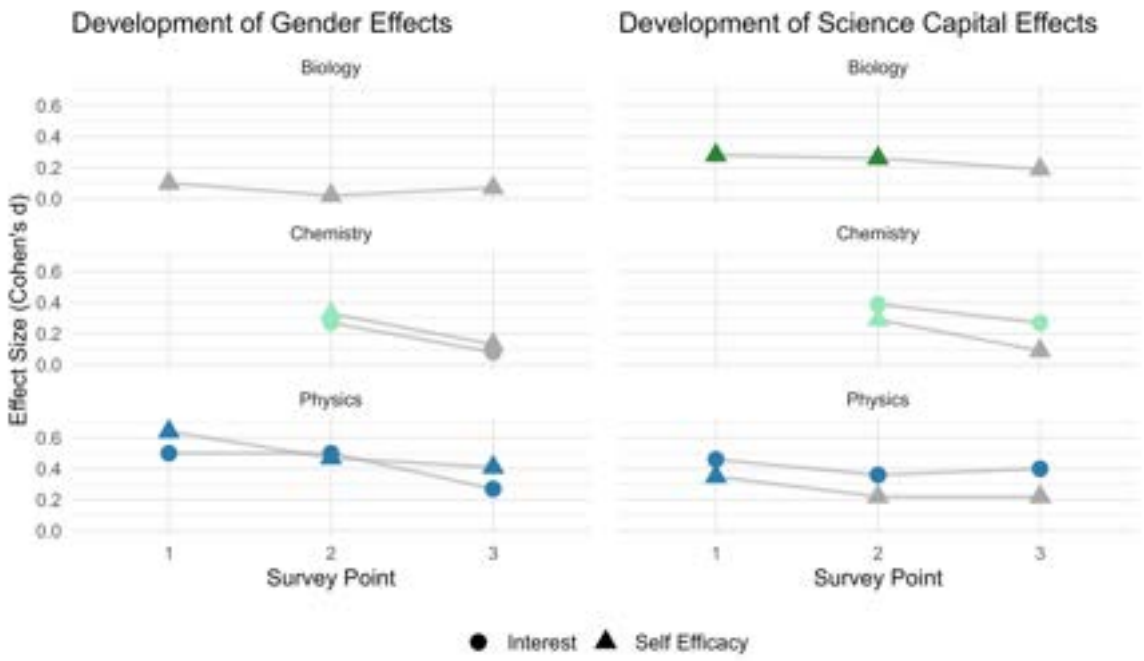


Discussion And Outlook

Our analyses show that gender and Science Capital perspectives are highly relevant in early science education. The findings indicate that the role of gender and Science Capital varies across different natural science subjects and develops differently during initial teaching (see Figure 4). Our results, covering the first two years of physics lessons and the first year of chemistry lessons, indicate that the differences diminish over time, although this is only achieved through a sharp decline in self-assessments that may have been overestimated. Physics-related constructs appear to be developing in a particularly problematic manner. Only in this subject does the gender gap remain significant at the end of our survey. It was also found that students whose parents both work in scientific professions do not exhibit higher self-efficacy or greater interest, meaning that the effects must be considered differently depending on the strength of the parents' scientific background.

In addition to further analytical perspectives (e.g. peer influence, image of science), the next step is to move away from individual constructs and examine a more comprehensive construct of STEM identity (see e.g. Hazari et al., 2020) and its development in early science education. In addition, triangulation with the qualitative data from the project is planned in order to explain the developments identified.

Figure 4. Development of gender gap and Science Capital gap in interest and self-efficacy in biology, chemistry and physics. Grey colour indicates insignificant effects.



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Deconstructing Stereotypes: A Critical Approach To Indigenous Knowledge In Chemistry Education

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Indigenous peoples, estimated at over 300 million across all continents constitute the vast majority of the world's cultural diversity and act as primary guardians of socio-biodiversity, yet their epistemologies remain marginalized by colonial legacies. In the Brazilian educational context, marked by the historical invisibility of indigenous peoples, this research addresses the need to deconstruct stereotypes in Chemistry teaching. Grounded in Law No. 11,645/2008 and decolonial perspectives, the study emerges from the gap in indigenous thematic integration within the scientific curriculum. The theoretical framework is anchored in Critical Meaningful Learning and intercultural theories that question epistemological hierarchies. This paper presents a theoretically validated pedagogical model, focusing on its didactic architecture rather than classroom implementation. The central research question interrogates: In what way can a Potentially Meaningful Teaching Unit (PMTU), structured under decolonial perspectives, provide a methodological framework for integrating Indigenous themes into Chemistry and overcoming curricular fragmentation? By structuring the PMTU through decolonial lenses, this study provides educators with a robust and replicable framework to operationalize the inclusion of Indigenous knowledge, offering a concrete methodology to mitigate the historical invisibility of these epistemologies. The proposal promotes an integrative reconciliation between scientific and traditional knowledge, fostering a contemporary understanding that recognizes epistemological diversity. Designed for adaptation to various global contexts, this framework favours the valorisation of Indigenous peoples and promotes a restorative, truly intercultural science education.

Keywords: Epistemological Pluralism; Interculturality, Epistemic Justice.

Introduction

Brazil, a territory originally inhabited by hundreds of indigenous peoples with millennial linguistic, cultural, and traditional knowledge diversity, still bears deep marks of the colonial process in its educational system. These marks manifest themselves in the marginalization of indigenous history, cultures, and knowledge in school curricula, perpetuating stereotypes and reductionist views, disqualifying traditional methods of knowledge transmission, and privileging Western scientific knowledge; resulting in epistemological violence and historical erasure. Such invisibility compromises the very understanding of Brazilian history by disregarding these peoples' millennial contributions to society's development (Baniwa, 2025; Kayapó, 2021; Munduruku, 2020) and ignores the contemporary, dynamic, and diverse presence of more than 279 indigenous peoples in present-day Brazil (Brazilian Institute of Geography and Statistics [IBGE], 2022).

This dynamic constitutes a profound form of epistemic injustice. As Yarbrough and Smith-Colin (2025) highlight, justice in this context involves correcting the "credibility deficit" imposed on marginalized groups. In science education, this means moving beyond the historical invisibility of traditional knowledge and recognizing Indigenous peoples not just as sources of cultural data, but as legitimate holders of expertise. Addressing this deficit is a restorative act, essential for a curriculum that seeks to repair the historical silencing and the "epistemic violence" often directed at original peoples (Potiguara, 2019; Yarbrough & Smith-Colin, 2025).

In the Brazilian context, this restorative effort finds a concrete expression in the recognition of Indigenous epistemologies. The cultural richness of the Indigenous peoples in Brazil is not

limited to the preservation of ancestral traditions but is manifested in complex systems of knowledge production that engage directly with science. As Law 11.645/08 indicates, the inclusion of this knowledge in the school curriculum is a fundamental step toward an anti-racist and decolonial education. This epistemological plurality challenges the hegemony of Eurocentric thought by highlighting the sustainable management of biodiversity and the social technologies developed by different ethnic groups (Munduruku, 2020; Krenak & Doyle, 2025). In the field of science education, this valorisation allows for what Vanuchi and Raupp (2025) characterizes as a necessary integration between scientific knowledge and Indigenous cosmovisions, promoting a scientific literacy that respects the alterity and cultural heritage of the Brazilian territory. In practice, this integration aligns this research with the concept of epistemological pluralism, which, as Morgan (2011) discusses, involves a shift away from a single, reductionist worldview toward an integrated perspective that values diverse ways of knowing. In Chemistry education, this pluralism acts as a 'corrective' to the limitations of Western science, allowing for a more holistic understanding of reality where indigenous perspectives on the environment and matter are not merely 'included' but are foundational to a broader scientific literacy.

This theoretical framework provides the necessary tools to address a historical context of struggle, where Indigenous and Black social movements have fought for recognition and appreciation of their contributions to Brazilian society's formation, an achievement breaks centuries of silencing and invisibility in the school environment: the enactment of Law No. 11,645 of March 2008, which mandates the teaching of Afro-Brazilian and indigenous history and culture in Basic Education school curriculum (Brasil, 2008). Although enacted nearly 16 years ago, little has been done to change the established scenario. Its effective implementation creates tension for a new positioning that involves questioning an educational model that not only promotes but also perpetuates these peoples' invisibility (Kayapó & Brito, 2014; Marques, 2014).

Furthermore, the challenge of integration is deeply tied to the universalist and Eurocentric view of modern science. However, contemporary studies reveal that Western science has always been spatially situated and dependent on its encounters with non-Western knowledge systems. The case of the Sámi people in Scandinavia demonstrates that "indigenizing" Western science is not about replacing it, but about recognizing it as an evolving intellectual culture that is modified by human and physical challenges posed by Indigenous residents (Wråkberg & Granqvist, 2014).

Under the premise that the inclusion of Indigenous themes is a vital strategy for this deconstruction within the Brazilian context, this study investigates how to operationalize such a dialogue through the following research question: In what way can a Potentially Meaningful Teaching Unit (PMTU), structured under decolonial perspectives, provide a methodological framework for integrating Indigenous themes into Chemistry and overcoming curricular fragmentation? This proposal was conceived as part of a doctoral research project in Science Education, developed at a public university in Southern Brazil.

Bridging The Gap: Challenges Of Law 11,645/08 In Chemistry

Despite legal requirements, a systematic review study (Vanuchi & Raupp, 2022) revealed a significant research gap in science education, where indigenous themes remain concentrated in arts, literature, and history disciplines, failing to achieve the transversality intended by Law 11,645/08. This gap is not merely a technical failure in curriculum design, but a reflection of deeper epistemological barriers. This concentration in non-scientific fields reinforces the stereotype of Indigenous peoples as historical or folkloric figures, lacking technical and scientific

agency. By failing to achieve transversality in Chemistry, the education system implicitly perpetuates the myth that Indigenous knowledge is incompatible with rigorous scientific thought.

Brazilian indigenous intellectuals point out critical challenges in implementing the Law in science education. Gersem Baniwa (2025) shows the persistence of structural obstacles to plural education due to the colonial nature of academic knowledge, while Daniel Munduruku (2019) emphasizes that effective implementation requires a curricular reconfiguration to include historically marginalized indigenous scientific practices. Ailton Krenak adds that the current system reproduces epistemic hierarchies that disqualify ancestral knowledge (Krenak & Doyle, 2025).

According to Eliane Potiguara (2019), genuine change will only occur through truly intercultural education that recognizes Brazilian epistemological plurality. Understanding the roots of this resistance requires considering the perspectives of Indigenous intellectuals who identify the colonial foundations of these educational obstacles. These Indigenous critiques are deeply aligned with the broader academic framework of critical interculturality, which provides the theoretical tools to dismantle the power structures that sustain such colonial resistance.

Interculturality represents a significant evolution in global academic thinking, based on fundamental contributions established in decolonial perspective foundations (Quijano, 2020). The field was enriched by critical analyses of subalternity and power structures that silence marginalized voices (Spivak, 1988), explaining how epistemological colonialism resulted in the exclusion of non-Western knowledge (Dussel, 2019). Furthermore, explorations of cultural hybridity and identity (Bhabha, 1994; Hall, 1996) contribute to deconstructing Eurocentric narratives and promoting knowledge decolonization, significantly influencing education and science (Mignolo, 2011). Such perspectives are essential for rethinking school curricula to recognize and value different epistemologies (Walsh, 2013).

However, there is still a long way to go to effectively incorporate indigenous contributions into pedagogical practices without limiting them to commemorative dates. Insufficient teacher training and undergraduate courses that rarely include indigenous themes remain major hurdles (Bergamaschi, 2012: Oliveira & Almeida, 2023). Teaching materials often reproduce stereotypes (Grupioni, 1995) and invisibilize contemporary indigenous scientific contributions by limiting these peoples to a colonial past (Kayapó, 2021; Munduruku, 2019). This institutional resistance to accepting non-Western epistemologies confirms that the coloniality of knowledge remains a formidable obstacle (Quijano, 2020; Walsh, 2013).

The analysis of these structural and epistemological barriers demonstrates that implementing Law 11,645/08 in Chemistry requires pedagogical tools that operationalize intercultural dialogue. Moving beyond normative guidelines, it is essential to develop strategies that challenge Eurocentric curricula and deconstruct deeply rooted stereotypes.

Proposal: A Didactic Strategy Based On Significantly Critical Learning

Acknowledging that interculturality requires a critical approach beyond simple content inclusion (Walsh, 2013), this didactic proposal is founded on Critical Meaningful Learning (Moreira, 2000; 2011), expanding upon Ausubel's theory (2012) by emphasizing learners' critical engagement with content through questioning its validity and contextual relevance to their sociocultural environment. In the context of this research, Critical Meaningful Learning (CML) is not merely a cognitive process but a political and ethical stance against the coloniality of knowledge. According to Moreira (2000; 2011), CML allows the learner to participate in their culture while simultaneously distancing themselves from it critically. For indigenous themes in Chemistry education, this means that students can recognize the historical stereotypes embedded in their

social fabric while using critical thinking to 'unlearn' folkloric representations—the 'generic indigenous' person—and anchor new meanings based on contemporary indigenous scientific contributions. This process of 'unlearning' serves as an epistemological break, essential for decolonizing the curriculum and acknowledging indigenous peoples as dynamic producers of knowledge rather than figures fixed in the past.

Within the scope of Chemistry education, addressing Indigenous themes acts as a catalyst for intercultural education by challenging the universalist and Eurocentric view of modern science. By integrating traditional knowledge, the curriculum shifts from being a transmitter of abstract concepts to a space for dialogue between different forms of knowledge. This pedagogical practice, grounded in decoloniality, allows students to recognize Chemistry as a plural human construction, where Indigenous social technology is validated as legitimate scientific knowledge. In this way, chemical education contributes to the recognition of alterity, promoting respect for diverse ways of interacting with matter and the environment, which are fundamental pillars for a truly intercultural society.

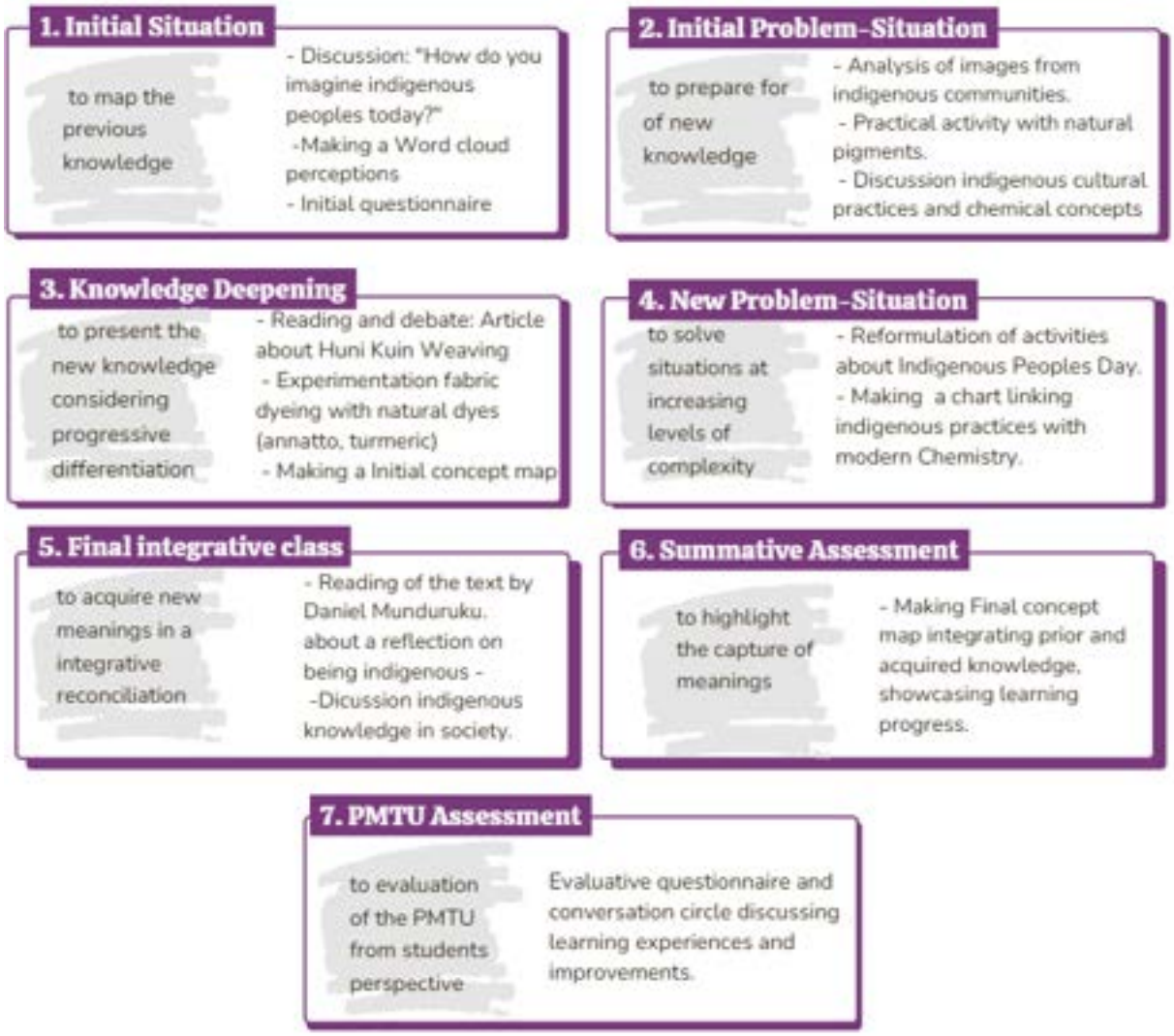
In order to transform this theoretical critique into a structured learning experience, the proposal is materialized through Moreira's (2011) Potentially Meaningful Teaching Units (PMTU) framework. This methodology utilizes logically structured, meaningful materials specifically designed for the target audience to promote meaningful rather than mechanical learning. Consequently, PMTUs facilitate a higher quality of knowledge. Briefly, the PMTU is composed of the initial situation: which aims to map the previous knowledge of students. Initial problem-situation: a problem-situation of an introductory level, seeking to give meaning to the concept. Deepening of knowledge: approach from progressive differentiation. New problem situation: questions with a higher level of depth, evidencing the correspondences and contradictions between the concepts. Individual summative evaluation: test evidencing the capture of meanings. Final integrative class: seeks integrative reconciliation between concepts. Learning assessment: evidence should be sought for understanding meanings and the ability to use knowledge for different situations throughout the implementation of the PMTU, focusing on collaborative activities, and ending it with an individual summative assessment. Evaluation of the PMTU itself: In order to improve teaching strategies, to assess the perspective of students (Schittler; Moreira, 2014).

The PMTU methodology comprises seven progressive stages supported by formative assessment (Figure 1), utilizing problem-based situations to evaluate the acquisition of meanings. Although this proposal is grounded in the Brazilian legal framework (Law No. 11,645/2008), its methodological structure is designed to be flexible, adaptable, and replicable in diverse international contexts. The core objective — the integrative reconciliation between Western scientific language and ancestral epistemologies — addresses a global challenge in science education: the need for pluralistic and intercultural curricula that respect local identities while promoting scientific literacy.

The sequence of activities comprised in the PMTU is detailed below, highlighting the pedagogical intent of each stage and its alignment with the goals of decolonial science education

1. Initial Situation: designed to identify students' prior conceptions, which are often permeated by colonial stereotypes. This diagnostic phase is crucial for the subsequent pedagogical insurgence, allowing the instructor to confront biased views with the complexity of Indigenous social technologies. We suggest three instruments: (1) a collective debate focused on students' perceptions of Indigenous peoples in contemporary times; (2) the collaborative construction of a word cloud using digital tools; and (3) an individual questionnaire exploring the understanding of Indigenous peoples in the present day and the recognition of Indigenous cultural heritage.

Figure 1. PMTU Organization with definition of the seven progressive stages, selected activities and didactic resources.



2. Initial Problem-Situation: the goal is to provoke a critical confrontation between colonial imaginaries and the diversity of Indigenous identities using image analysis (Figure 2). A stereotypical depiction showing reductionist folkloric views (nudity, straight hair, uniform skin tone, headdresses, and life restricted to nature) and Ailton Krenak, who challenges limiting perspectives by occupying prominent spaces, such as the Brazilian Academy of Letters.The proposal operationalizes what Walsh (2013) terms 'pedagogical insurgence.' Methodologically, this stage initiates the process of progressive differentiation, challenging the 'epistemic violence' (Spivak, 1988) that historically relegated Indigenous existence to a static past, thereby opening space for the recognition of Indigenous peoples as contemporary producers of knowledge and science.

The stage suggests an experimental activity (Vanuchi & Braibante, 2021) preparing natural dyes using genipap and annatto - pigments traditionally used by indigenous peoples for ritual and identity markings (Figure 3). This stage operationalizes integrative reconciliation (Moreira, 2011) by connecting traditional Indigenous knowledge with scientific concepts of Organic Chemistry. The preparation of natural dyes from genipap and annatto substances historically used for ritual and identity markings—serves as a critical subsumer.

The role of this stage is to validate ancestral knowledge as complex technoscientific systems, allowing students to understand chemical phenomena (such as polarity and functional groups) from a culturally relevant basis, effectively deconstructing the view of Indigenous knowledge as merely folkloric.

Figure 2: Stereotyped Indigenous Person vs. Contemporary Indigenous Person.



Figure 3: The use of natural pigments in body ornamentations.



3. Knowledge Deepening: discussion of the article about Huni Kuin (Silva et al, 2016) weaving and the complex textile production techniques of this ethnicity, in a progressive differentiation when general concepts progressively broken down into more specific concepts (Moreira, 2011), showing how this knowledge is closely linked to various chemical concepts, such as acids and bases, pH, intermolecular forces, and mixture separation techniques, like decantation and filtration, maceration processes, decoction. Each ethnicity develops its own techniques and symbologies for the extraction and use of pigments (Figure 4) that not only decorate but carry deep cultural meanings.

Figure 4. Fabrics dyed with annatto.



The role of this phase is to demonstrate that each ethnicity develops specific methodologies for pigment extraction. This approach reinforces the deconstruction of stereotypes by moving from

a general appreciation of Indigenous culture to a rigorous technical understanding of their scientific contributions

4. New Problem-Situation: in greater level of depth, students will be encouraged to critically reformulate commonly used stereotypical school activities, especially those related to "Indigenous Peoples Day" (Figure 5). After, they will also organize a flowchart that relates indigenous knowledge, natural pigments, and Chemistry principles, promoting an integrative reconciliation between traditional and scientific knowledge.

Figure 5. School activity on April 19th in homage to the First Inter-American Indianist Congress, held in 1940, with stereotypical representations that reinforce misconceptions about these peoples.



April 19th
Indian Day

Indians were the first inhabitants of Brazil
In the beginning, there were many Indians living free in our forests.
Today, they are very few in number.
Indians live in groups called tribes.
Each tribe has a warrior chief, called cacique or morubixaba,
and a religious leader, called a shaman, who is also the tribe's healer.
The Indians' houses are called hollows. These are huts built with
sticks and clay, covered with straw or tree leaves.
The gathering of hollows forms a small village,
called taba.
The weapons of the Indians are the bow, the arrow, the
spear, club and blowgun.
Indians usually sleep in hammocks or
mats.
They feed on hunting, fishing and vegetables.
They plant cassava, corn, sweet potatoes, etc.
They like to sing and dance. Your
musical instruments are the drum, the rattle, the
flute and maraca.
The Indians are naked or almost naked. Some
wear loincloths and headdresses made of colourful feathers
birds.
They usually paint their bodies with dyes extracted
of plants.
They adorn themselves with necklaces and bracelets made from
animal teeth.
They worship the sun, which they call Guaraci, the moon,
which they call Jaci, and other gods.

Dia 19 de Abril
Dia do Índio

Os índios foram os primeiros habitantes do Brasil.
No começo, havia muitos índios vivendo livres nas nossas florestas.
Hoje, eles são em número bem reduzido.
Os índios vivem em grupos chamados tribos.
Cada tribo tem um chefe guerreiro, chamado cacique ou morubixaba,
e um chefe religioso, chamado pajé, que também é curandeiro da tribo.
As casas dos índios chamam-se ocas. São cabanas construídas com
paus e barro, cobertas de palha ou folhas de árvores.
A reunião de ocas forma uma pequena aldeia
chamada taba.
As armas dos índios são o arco, a flecha, a
lança, o tacape e a zarabatana.
Os índios costumam dormir em redes ou
esteiras.
Alimentam-se da caça, da pesca e de vegetais.
Plantam mandioca, milho, batata-doce, etc.
Gostam de cantar e de dançar. Seus
instrumentos musicais são o tambor, o chocalho, a
flauta e o maracá.
Os índios andam nus ou quase nus. Alguns
usam tangas e cocares feitos de penas coloridas de
aves.
Costumam pintar o corpo com tintas extraídas
das plantas.
Enfeitam-se com colares e pulseiras feitos com
dentes de animais.
Adoram o sol, que chamam de Guaraci, a lua,
que chamam de Jaci, e outros deuses.

This stage aims to combat curricular fragmentation and the 'folklorization' of Indigenous themes, which are often restricted to isolated commemorative dates such as 'Indigenous Peoples Day.' By encouraging students to critically reformulate stereotypical school activities, the proposal operationalizes the challenge of moving beyond mere symbolic inclusion. The role of this phase is to promote a final integrative reconciliation, where traditional knowledge and chemical principles are organized into a flowchart of interdependence.

5. Final Integrative Class: discussion of the text "I can be who you are without ceasing to be who I am: a reflection on being indigenous" by Daniel Munduruku in a circle, to reflect on the presence and valorization of indigenous knowledge in/by contemporary society and science.It demands an integrative reconciliation - the construction and reconstruction of conceptual relationships, as new concepts were incorporated into the cognitive structure and need to be reorganized (Moreira, 2011).

6. Summative Assessment: Construction of a final conceptual map with the focal question: What knowledge do you have about Indigenous peoples and their role in contemporary society? By comparing both maps, it will be possible to observe progressive differentiation and integrative reconciliation, as well as identifying changes in students' representations of Indigenous peoples.

7. PMTU Assessment: An evaluative questionnaire for feedback and a discussion circle to reflect on how students' perceptions of Indigenous peoples have changed and how this new perspective has impacted their understanding of Chemistry.

The integration of these seven stages within the PMTU framework transcends a mere instructional sequence; it constitutes a deliberate pedagogical intervention aimed at fostering anti-racist and intercultural chemistry education. By centering Indigenous social technologies, such as the chemistry of natural pigments, this strategy operationalizes what Walsh (2013) defines as 'pedagogical insurgence,' challenging the Eurocentric hegemony that historically silenced non-Western forms of knowing. The iterative cycle of problem-situations and integrative reconciliation provides the necessary scaffolding for students to recognize 'epistemic pluralism' (Baniwa, 2025), acknowledging Indigenous peoples as contemporary producers of scientific knowledge rather than figures of a folkloric past. Consequently, this didactic approach acts as a restorative practice, aligning chemical concepts with social justice to deconstruct racialized hierarchies and promote a more equitable and pluralistic understanding of science (Munduruku, 2019; Quijano, 2020).

Within the scope of Chemistry education, addressing Indigenous themes acts as a catalyst for intercultural education by challenging the universalist and Eurocentric view of modern science. This challenge is supported by the understanding of technoscience, which reveals that Western science has historically been dependent on and shaped by its encounters with non-Western knowledge systems (Wråkberg & Granqvist, 2014). By integrating traditional knowledge—such as natural pigment extraction and textile production techniques (Silva et al., 2016)—the curriculum shifts from a transmitter of abstract concepts to a space for 'indigenizing' Western science. This process transforms colonial science into a tool for emancipation (Baniwa, 2025; Walsh, 2013), where Indigenous social technology is validated as a legitimate scientific contribution that modifies and enriches global scientific practices.

Final Considerations

This research addressed the persistent challenge of integrating Indigenous themes into the Chemistry curriculum, a field historically dominated by Eurocentric and universalist perspectives. By developing a didactic strategy grounded in Potentially Meaningful Teaching Units (PMTU) and Critical Meaningful Learning, we demonstrated that it is possible to move beyond the mere fulfilment of Law 11,645/2008 toward a practice of epistemic justice.

The proposal, by centring Indigenous social technologies, served as a catalyst for decolonizing the science curriculum. This process allowed for the deconstruction of folkloric stereotypes, positioning Indigenous peoples not as relics of the past, but as dynamic producers of contemporary scientific knowledge. A key contribution of this study is the structural flexibility of the PMTU framework, which is designed to be adaptable and replicable in diverse international contexts. This allows the methodology to be tailored to the specific scientific realities and ancestral epistemologies of different Indigenous peoples across various global regions. Although the results of the evaluation of the UEPS have not yet been systematized, this proposal outlines the theoretical and methodological foundations that will guide this stage. The different phases of the UEPS — which range from the assessment of prior knowledge to problematization and integrative reconciliation — were organized to facilitate the identification of possible changes in students' understanding of Indigenous peoples and the chemical concepts addressed throughout the proposal.

In conclusion, this proposal aims to contribute to the global dialogue on Diversity, Identity, and Inclusion in Science Education by offering a validated and structurally flexible methodology. A key contribution of this framework is its potential for adaptation; it is designed to be replicable in diverse international contexts, allowing the pedagogical stages to be tailored to the specific scientific realities and ancestral epistemologies of different Indigenous peoples across various

global regions. Thus, decolonizing Chemistry teaching is presented not only as a local necessity but as a global opportunity to honor epistemological plurality and promote the inclusion of historically marginalized voices in the scientific field.

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How Families' Everyday Engagements Hold Potential For Cultivating Students' Science Capital And Align With School Science

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This study investigates how students' everyday activities outside school, across family contexts, hold potential for shaping distinct forms of Science Capital and how these forms can align with school science. The findings are based on 54 interviews with Danish families of students aged 6 to 15 from five schools.

While family life encompasses a wide range of science-related experiences, these activities are often not recognized or framed as relevant to formal education. Instead, parents primarily value these experiences for fostering lifelong skills, personal development, family bonding, and well-being. In addition, family engagement in science-related activities often involves sensory, creative, and aesthetic interactions with natural objects and phenomena, which contrast with the academic approaches emphasized in science education.

Finally, our results reveal that parents' valued childhood leisure experiences, interests, values, knowledge, and skills, together with opportunities afforded by place and local surroundings, influence how science is approached, discussed, and enacted within families.

Consequently, the ways students engage in science-related activities vary across family contexts, leading to different degrees of alignment between students' science experiences outside school and school science. These findings show that students' family experiences play a critical role in shaping the forms of Science Capital they bring into the classroom and how these forms are recognized within school science. The results highlight the importance of aligning science education with students' everyday lives to foster more relevant and inclusive school science. A "Science Capital Teaching Approach" is discussed as a framework for bridging students' experiences with school science.

Keywords: Family Science Habitus, Science Capital, School Science

Introduction

Science education has been criticized for reinforcing systemic inequalities by failing to recognize and address the diversity in students' family contexts. It has been suggested that the misalignment between students' family engagement and school science maintains disparities in participation, engagement, and achievement (Nomikou, Archer, & King, 2017). Recent TIMSS findings highlight these issues, revealing significant inequalities in science achievement linked to family background. Notably, some countries, including Denmark, have experienced an increase in these disparities in recent years (von Davier, Kennedy, Reynolds, Fishbein, Khorramdel, Aldrich, Bookbinder, Ummugal, & Yin, 2024). To understand these inequalities, this study draws on the concepts of Science Capital and family science habitus, as well as the interplay between the two.

Science Capital

Science Capital can be defined as an individual's science-related knowledge, attitudes, and experiences. It is argued that students' Science Capital plays a crucial role in shaping their opportunities to develop a strong science identity, engage with school science, and pursue future

aspirations (Archer et al., 2015). However, not all forms of Science Capital hold the same exchange value in school science. Certain forms - such as knowing scientific concepts - are more likely to be recognized and valued as Science Capital in school. In contrast, more applied forms - such as engaging in gardening, repairing machines, or cooking - often remain invisible within school science (Nomikou, Archer, & King, 2017).

Family Science Habitus

Families play a critical role in shaping students' engagement with science through their values, attitudes, and everyday practices, which can be understood as family habitus (Archer et al., 2012). Family habitus influences how students perceive and relate to science; however, not all forms of family habitus align equally well with the norms and practices of conventional science education (Archer et al., 2012; Suortti, Havu-Nuutinen, & Kärkkäinen, 2023).

In this way, the concept of family habitus is not only useful for understanding how and why science is embedded in everyday family life but also for examining how its alignment - or misalignment - with school habitus (i.e., the norms and curricular expectations of school science) can reinforce or mitigate inequalities in students' ability to relate to, participate in, and benefit from science education.

The Interplay Between Family Habitus And Science Capital

Family habitus and Science Capital are closely interrelated concepts, and their interplay is important for understanding how family everyday life shapes students' opportunities to participate in, benefit from, and relate to school science. Indeed, it is argued that family habitus cultivates different forms of Science Capital, each carrying varying degrees of potential to be recognized and valued within school science (Archer et al., 2012).

This means that family habitus directly influences students' engagement in school science through its alignment - or misalignment - with school habitus. Additionally, it indirectly shapes the types of Science Capital students develop, which in turn affects their participation and success in science education. Ultimately, these outcomes depend on both the degree of alignment between home and school habitus and the extent to which students' different forms of Science Capital are recognized within the field of school science.

Taken together, students enter science classrooms with varying possibilities to relate to, engage with, and participate in science education, depending on how their family science habitus and the form of Science Capital cultivated in their everyday science engagement align with school science expectations. This leads to unequal opportunities for students to fully access science learning and perceive it as meaningful and relevant to both their present and future lives. Ultimately, the interplay between family habitus, the development of Science Capital, and its alignment with school science has significant implications for students' participation, success, and long-term aspirations in science.

By exploring how family science habitus cultivates different forms of Science Capital, this study addresses a rarely explored perspective in science education research, as called for by the science research community (Wenner, 2024). This article argues that understanding how and why families engage with science-related activities is essential for fostering more inclusive and equitable science education, particularly for a more diverse group of students.

Against this background, we set out to answer the following research question:

How and why do families engage with science-related activities – and in what way does this engagement hold potential for cultivating different forms of students' Science Capital, and how do these forms of Science Capital align with school science?

Research Methods

Data were collected through interviews with families of students from five Danish schools, selected to ensure diversity in geography, urbanity, and students' socioeconomic and ethnic backgrounds. Using a maximum variation sampling approach, 15 students were selected from each school across grades 0, 5, and 8. Of the planned 75 interviews, 54 were successfully conducted. Interviews took place in families' homes, with primary caregivers (predominantly parents) serving as the main informants, while in most cases, the student and occasionally their siblings also participated. In a few cases, interviews were conducted online or at an alternative location chosen by the family for reasons of comfort or practicality.

The interviews were guided by a semi-structured interview protocol and a "family wheel poster", which illustrated physical and temporal aspects of families' everyday lives. The questions were informed by a conceptual framework combining Science Capital and family science habitus (e.g., Jones, Ennes, Weedfall, Chesnutt, & Cayton, 2021). Additionally, families were presented with photos depicting various science-related places and activities to prompt reflections and discussions about their experiences, perceptions, and attitudes toward science.

Throughout the interviews, family members and the interviewer jointly contributed to the family wheel with drawings, comments, and examples. All interviews were recorded, transcribed, and analysed using a combined deductive and inductive thematic analysis approach (Braun & Clarke, 2006). For illustration, an example of a deductive code related to Science Capital was "Access to physical science-related resources" (e.g., 3D printers, greenhouses, pets/livestock). In contrast, an inductive theme that emerged was "Togetherness and Shared Experiences," capturing parents' rationale for engaging in science-related activities with their children.

Results

First, we describe the dominant pattern across families, showing how science-related engagement is embedded in everyday life without being articulated as ‘science’. We then examine how this engagement is shaped by parents’ interests and place, and how it is characterized by embodied, sensory, and lived experiences. Finally, we highlight important variations across families, where some everyday practices come to resemble ways of engaging that align more closely with school science, pointing to differences in how students’ Science Capital is likely to be recognized within school science.

Science As Part Of Everyday Family Life

The findings indicate that, although family everyday life involves a wide range of science-related individual activities (e.g., jewelry crafting, taking mobile snapshots, strength training) and collective activities (e.g., forest outings, cooking, hunting/fishing, gardening, tractor drags, collecting natural artifacts, home repairs), these activities are often not recognized, connected to, or framed as relevant to school science by the families.

Parents’ Interests Shaping Shared Family Activities

Furthermore, while parents support their children’s individual interests, both parent-child activities (e.g., horseback riding, hiking) and organized leisure activities (e.g., team sports, scouting) often reflect parents' own valued childhood pursuits. The following example illustrates how a shared leisure interest becomes a practice passed on across generations within the family:

(Family A; Girl, 7 years)

> Father: “My father collected a lot of model airplanes … and that definitely helped build my interest in airplanes, one hundred percent. If he hadn’t done that, I wouldn’t have had that interest.”
>
> Mother: “…dad is very interested in model airplanes it’s really his big thing. This used to be an old guild hall that we turned into a hobby room, and that’s where he spends time tinkering. He’s very interested in technology. You’re a bit into that too, aren’t you? You also think it’s fun, this whole model airplane camp and things like that, right?”
>
> Girl: “Yes.”
>
> Mother: “[…] she is probably the one who is most interested in the airplane stuff and all of that - I honestly don’t understand a thing about it, but she really wants to.”

Additionally, parents' personal interests (e.g., gardening, building airplanes, birdwatching, and home repairs), values (e.g., viewing nature as a space for well-being and seeing practical skills as important), skills (e.g., recognizing species, using tools), and attitudes (e.g., sharing enthusiasm and inviting children to participate without obligation) strongly influence the shared experiences children are invited to take part in as part of everyday family life. In several families, this became clear through everyday workshop activities, where children participated alongside their parents in making, repairing, and constructing things together:

> (Family B; Boy, 7 years)
> Boy: “Sometimes, when I hear a hammer, I come.”
> Father: “Then we go down to the basement together, and you bring out your toolbox, where you can saw and screw.”
> Boy: “I even have an old-fashioned drill.”

This example shows how parents’ everyday engagement in making and repairing, together with the availability of tools and workspace in the home, naturally draws children into these activities as part of family life.

In another family, this everyday engagement appeared in time spent together outdoors:

> “It is more about observing. I have done that since I was a boy. I was involved in nature associations for young people and the Danish Ornithological Society to watch birds. I am not part of an organization anymore, but I still look for birds. These things still fill a lot for me - plants, animals, mushrooms, birds. We sometimes go on trips to the forest to collect mushrooms or go out to look at birds and plants. If we find a mushroom, I like to show it to the children. There is always a kind of excitement in finding things. I get enthusiastic about it, so I would like to share it with them. They should have the opportunity. If they are not interested, they can just say so.” (Father, Family C; Girl, 12 years)

Together, these accounts show how parents’ own interests, values, skills, and attitudes shape how families spend time together. What began as a parent’s own long-standing interest becomes visible in shared activities, in what the family stops to look at, and in how time is spent together. Whether through shared making in a workshop or shared attention to birds, plants, and mushrooms, children participate in activities that emerge from what is natural to the parents themselves in everyday family life. In this way, children are drawn into these practices through parents’ enthusiasm and repeated shared experiences rather than through planned learning situations.

Nature As Lived, Sensory And Creative Experience

Our data suggest that when children engage in science-related activities within the family, parents do not primarily focus on enhancing their children's school science performance or fostering aspirations in science. Instead, parents value these activities for their perceived contributions to lifelong skills for everyday life and personal development, fostering bonds within the family and friendships through shared experiences, and promoting physical and mental well-being.

One father explained, in response to how nature is approached and valued within the family:

> "Nature is basically the foundation of where we come from. If you become aware that everything around us originates there in its original form, it gives a better understanding of environmental conditions and of how to act responsibly in relation to what we eat and how we cultivate the land. It is also something spiritual and related to well-being. Being in nature gives an inner calm that you do not find in hectic surroundings. But it is difficult to have those kinds of conversations with children because it becomes too abstract. I think it comes by itself without having to say it. You develop an awareness of animals, plants, and the landscape simply by being in it. When we go out to pick blackberries or mushrooms, you get a closer relationship to nature that way."
>
> (Father, Family C girl grade 5)

This account illustrates how nature is understood as a meaningful and lived part of everyday family life. These understandings develop through shared activities rather than explicit explanation, as children participate in practices such as being outdoors and foraging together with their parents.

The Role Of Place And Access To Local Environments

Likewise, family science engagement is strongly shaped by place of residence, as geographical location, urbanity, and community resources influence opportunities. Indeed, access to organized leisure activities, playgrounds, home gardens, and natural areas affects both the frequency, diversity, and content of families' science-related experiences. The following example illustrates how access to local natural environments shaped and continues to shape families' everyday opportunities for science-related experiences:

> "We live in the last row of houses, and then you just walk out onto the heathland and further out onto the spit. It's incredible. I have never seen so many birds as after we moved there […] We have even been out looking for amber in the evenings when it's dark, and it's fascinating how the whole beach changes when night falls […] If the weather was good, we would suddenly go to the beach or go fishing […] We would often just go to the beach together. It takes two minutes and then we are there."
>
> (Mother, Family D; Boy, 7 years)

Or another family, referring to a nearby managed recreational nature park:

> "We have a dog, and I love going for long walks. We walk a lot out there - it's basically our backyard. I love it, so I am outside a lot." (Girl, Family E; 11 years)

Together, these accounts show how proximity to local natural environments makes spontaneous visits part of everyday life and a regular way of being. Rather than organized outings, the local landscape becomes a natural extension of the family's living space, offering ongoing opportunities to notice, explore, experience, and come to value the richness of this environment.

Nature As An Embodied, Sensory, And Lived Experience

In addition, our findings show that most families engage with natural objects and phenomena through multisensory, physically embodied, aesthetic, and sometimes creative approaches:

> "During the storm we were completely covered up with goggles… and the sand was hitting us. It was wild, but also fascinating to be right in it […] We experience so many things… and you don't have time to take pictures. You simply have to be in it […] I enjoy going to the beach and finding things we can use for something - creating something out of what we find."
>
> (Mother, Family D; Boy, 7 years)

Taken together, these accounts illustrate how family engagement with nature can be simultaneously sensory, physically embodied, place-based, and creative. They also show how such experiences are valued as lived moments that do not need to be documented, but rather fully experienced as they unfold.

Everyday Practices Resembling School Science

Finally, although the findings indicate that parents do not explicitly frame or value family activities in relation to school science, they still highlight differences linked to alignment with school science. For example, parents with backgrounds in science, technology, or pedagogy are more likely to engage in science-related activities in ways that resemble a school-oriented perspective. This includes practices such as naming natural objects, fostering curiosity, searching for information, and encouraging children to identify what they encounter in nature:

> "We really enjoy going out to explore and discover new places. It is very much about nature and experiencing different local areas. When the children were younger, they loved going to the pond to look for small animals. In the spring, we would run out and turn over the same tree stump, waiting for insects to appear. They are still very good at noticing butterflies and insects. For example, my son once found a beautiful caterpillar and really wanted to look it up to find out what kind it was. I can even remember the name of it. That is typically what we would do at home - try to identify what we find." (Mother, Family F; Boy, 12 years)

Similar patterns appeared in other families: *"It is mostly when we are out walking that you ask, 'Can you remember what this flower is called*?'" (Boy, Family G, 13 years). "*Yes, because I find it a bit embarrassing if they cannot remember*." (Mother, Family G, Boy, 13 years) or

> "We sometimes go on trips to collect mushrooms or look at birds and plants, and I always bring a mushroom guidebook to figure out what we find. The children sometimes find it exciting to search for things, sometimes they do not." (Father, Family C; Girl, 12 years).

In some families, this school-oriented perspective was also supported through the use of books and shared reading about nature at home as part of everyday activities:

> "When she was very little, we used to read those bird books… she found that really fun […] We would sit with books and read about all the sea animals… and at one point you even said yourself that you wanted to be a marine biologist" (smiling). (Family A; Girl, 7 years)

Together, these examples show how everyday walks and explorations in nearby nature involve paying attention to, noticing, identifying, and sometimes seeking further knowledge about what is encountered - including through books and shared reading at home. They indicate that being able to notice, recognize, name, and know elements in nature holds value within these families. In this way, everyday activities come to resemble the noticing, inquiry-oriented, and knowledge-seeking practices typically associated with school science, even though the activities themselves are not framed as such by the parents.

While some families in this way engage in practices that resemble a more school-oriented approach to science, the overall and more dominant pattern across families is that science-related engagement is embedded in everyday life without being articulated or valued as ‘science’.

At the same time, the findings show that science is enacted differently across families. How children encounter science in everyday life depends on parents’ interests, values, skills, long-standing engagements - often rooted in their own childhood and youth - as well as on the opportunities afforded by place and local surroundings.

As a result, children encounter science in different ways in everyday family life, with varying potential for alignment with school science.

Discussion And Conclusion

Our findings show that families possess substantial amounts of Science Capital, but that this capital appears in highly diverse forms. Rather than being expressed through formal scientific knowledge, Science Capital is embedded in everyday practices shaped by parents’ interests, values, skills, and long-standing engagements, often rooted in their own childhood experiences, as well as by the opportunities afforded by place and local surroundings. In this way, family science habitus plays a central role in shaping how science is enacted, talked about, and experienced in everyday life. As a result, children develop different forms of Science Capital depending on the form of family habitus within which they grow up, and thus enter school with varying forms of Science Capital, each with different degrees of alignment with school science (Archer et al., 2012; Suortti, Havu-Nuutinen, & Kärkkäinen, 2023).

These findings contribute to a more nuanced understanding of how family science habitus cultivates diverse forms of Science Capital. Indeed, this study indicates that family habitus functions as a key mechanism through which certain forms of Science Capital are developed, while others remain less likely to emerge.

At the same time, the findings point to a need for a broader understanding of what Science Capital can look like in everyday family life. In most families, Science Capital is not expressed through explicit science talk, visits to science institutions, or articulated interest in science. Instead, it appears as sensory, place-based, embodied, and practice-oriented engagements with natural phenomena and materials, often without being recognized or described as ‘science’ by the families themselves. These forms of engagement challenge common indicators of Science Capital found in previous research and suggest that Science Capital may be present in ways that remain largely invisible when viewed through traditional lenses.

In line with the Science Capital Teaching Approach (Nomikou, Archer, & King, 2017), our findings point to an untapped potential in linking students’ family experiences, local surroundings, and everyday practices to school science. By personalizing, localizing, and grounding school science in students’ sensory and lived experiences, science education can move towards a more inclusive understanding of what counts as science and who can participate in it.

Such an approach can help bridge the gap between students’ family science habitus and school science habitus by bringing a broader and more diverse range of students’ Science Capital into classroom practice, enabling more students to experience science as relevant to their lives and to recognize their own valuable contributions.

Acknowledgment

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Barriers In The Planning Phase Of Open Inquiry-Based Learning: Analysis From The Perspective Of Inclusive Science Education

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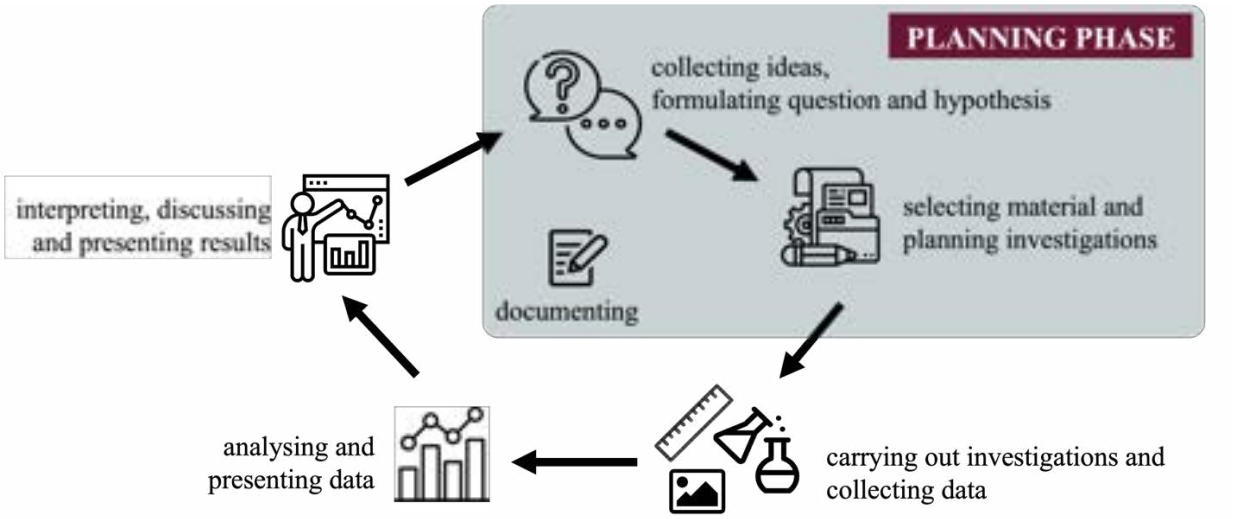
Open Inquiry-Based Learning (oIBL) offers a flexible, inclusive approach to science education by allowing students to construct knowledge through self-directed inquiry while engaging in scientific practices. A critical determinant of successful oIBL is the planning phase, which involves the core activities [A1] generating research questions, [A2] formulating a theory-driven assumption or hypothesis, and [A3] planning appropriate investigations. Challenges in this phase can negatively affect subsequent inquiry stages and student learning, and are often attributed to perceived deficits in student competencies. However, such a student-centred perspective overlooks barriers inherent to the activities themselves. This study addresses this gap by systematically identifying the requirements and challenges associated with the planning phase of oIBL and reframing them as object-related barriers – barriers rooted in the structure and characteristics of the subject matter. Using a scoping review, qualitative content analysis, and AI-assisted rephrasing, requirements and challenges for the three core activities [A1], [A2] and [A3] were extracted, analysed, and categorised. Key findings reveal that many barriers arise from subject-specific demands, methodological constraints, and the empirical nature of inquiry, rather than from students' skills alone. Reformulating challenges in this object-oriented manner supports the development of targeted, inclusive scaffolding materials. Future steps include expert validation, implementation, and evaluation of these materials, which will be made freely available as Open Educational Resources (OER) under a CC-BY license on the platform "twillo". The results highlight the importance of shifting from a deficit-oriented to a systemic perspective in analysing barriers of oIBL, enabling educators to address structural barriers and better support diverse learners in scientific inquiry.

Keywords: Open Inquiry-based Learning, Barriers, Inclusive Science Education, Diversity

Introduction

With the function as an inclusive instructional approach, open inquiry-based Learning (oIBL) can be used to incorporate subject-related aspects of diversity such as different procedural skills, subject specific knowledge, students' interests or prior experience. At the same time, oIBL offers students the opportunity to construct scientific knowledge and engage in scientific practices through an individually planned, self-determined and independently conducted approach in all phases of the inquiry process (e.g., Abrams et al., 2008). OIBL opens up for both individual and collaborative ways of inquiry learning (Liljeström et al., 2013) and promotes the development of problem-solving skills, while also fostering and requiring student motivation and creativity (Chin & Osborne, 2010; Jiang & McComas, 2015). A critical factor determining the success of the oIBL approach lies in the planning phase – the first phase of inquiry (Baur, 2018, 2021; Chen & Klahr, 1999; van Uum et al., 2017). As highlighted in Fig. 1, challenges particularly arise during this initial phase of oIBL, in which several key activities take place that are essential for its success (Hakkarainen & Sintonen, 2002): [A1] generating the research question, [A2] formulating a theory-driven assumption or hypothesis, and [A3] planning an appropriate investigation.

Figure 1. The planning phase of open IBL (adapted from Hofer & Abels, 2025).



Potential problems associated with these activities may not only negatively affect the quality of subsequent inquiry phases but may also hinder or delay students' acquisition of subject-matter knowledge (Hakkarainen & Sintonen, 2002). From the perspective of teaching, another challenge to the successful implementation of oIBL is the high demand placed on teachers in terms of subject-matter expertise and instructional experience. In addition, limited experience with the oIBL approach – on the part of both teachers and students – represents a further difficulty (Brand & Moore, 2011; Forbes et al., 2020; Hofer et al., 2018). Nevertheless, experience and knowledge of the fundamental principles of oIBL are crucial, as they enable the approach to function as intended and in its most effective form, namely as a flexible and adaptive learning environment (Hofer & Abels, 2025; Wischgoll et al., 2015). Such expertise is crucial for teacher-led support of students through appropriate scaffolding measures that are aligned with students' specific demands and needs (Arnold et al., 2014; Baur & Emden, 2021). For the realisation of a holistic oIBL approach combined with effective scaffolding, the teacher's role becomes particularly central – both in terms of designing and adapting the learning environment and in supporting students' individual inquiry processes through adaptive scaffolding (Hofer & Abels, 2025; Mumba et al., 2015; van der Valk & Jong, 2009).

The challenges that arise in oIBL are often attributed to individual students, with a primary focus on the perceived lack of competencies required to accomplish the task at hand (see Tab. 1). This perspective, however, neglects the fact that challenges do not emerge solely from students, but that barriers are inherent in the activities themselves. Abels and Witten (2023) argue that it would be more appropriate to move away from a student-centred perspective toward a systematic one (Köpfer, 2021), in which barriers are not primarily attributed to individual skill deficits but are instead located within the structure and characteristics of the subject matter. This object-oriented perspective suggests that subject matter should be analysed for potential barriers and hindrances that may impede learners' inquiry, while the instructional setting and learning environment are adjusted, adapted, and organised in a way that suits learners' diversity, needs, and strengths – rather than expecting only learners to adapt to requirements (Abels & Witten, 2023).

Table 1. Selected challenges for the activities of the planning phase of open IBL (selected from Kranz et al., 2023)

Phase	Challenge	Description
A1) generating the research question	Stating non-causal research questions	Learners only ask factual type questions that cannot be investigated by means of an experiment. Example of a factual-type question: How is a heart constructed? What is in this lotion?
A2) formulating an assumption or hypothesis	Working without a hypothesis	Learners do not generate hypotheses during the experiment.
A3) planning an investigation	Working without control conditions	Learners are just working with a single test condition and without a control (= results cannot be compared).

With this in mind, the project *PlanFoL – Auf die Planung kommt es an* (*Planning is Key*), which is funded by the Joachim Herz Foundation (2023-2026), aims to develop, test and evaluate practical cross-thematic support materials in order to reduce and address the barriers occurring in the planning phase of oIBL. Furthermore, the project explicitly focuses on a shift in the perspective regarding the attribution of challenges and barriers, respectively.

To do this, it is necessary to first identify the requirements and challenges of the planning phase and derive object-related barriers from them, which can then be addressed by the support materials. This raises the following research questions for the activities [A1] generating the research question, [A2] formulating a theory-driven assumption or hypothesis, and [A3] planning an appropriate investigation:

RQ1: Which requirements and challenges exist for the activities [A1-A3] in the planning phase of open inquiry-based learning?

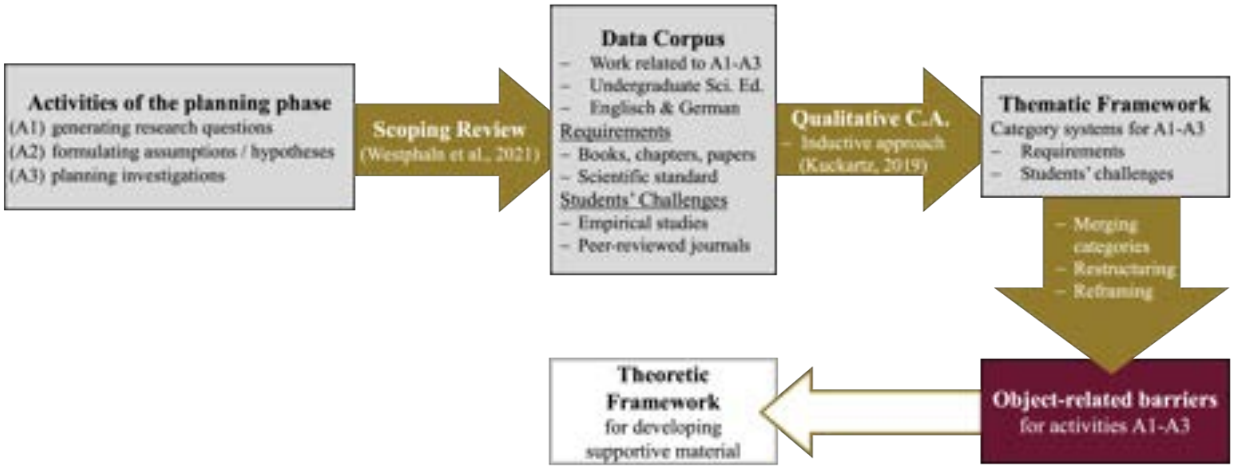
RQ2: What are the object-related barriers of the activities [A1-A3] in the planning phase of open inquiry-based learning?

Method

To identify the requirements and challenges associated with activities [A1]-[A3] in the planning phase of oIBL (RQ1), we first reviewed the existing literature (see Fig. 2). As a comprehensive and relevant systematic review on students' challenges in performing inquiry activities already existed (Kranz et al., 2023), we extracted the results relevant to the activities [A1]-[A3] and used them to address the aspect of "challenges" in the following research process.

To gain comprehensive theoretical insights into the "requirements" of activities [A1]-[A3], we conducted a scoping review following the approach proposed by Westphaln et al. (2021). Initial exploration of the literature indicated that requirements for activities [A1]-[A3] are not addressed explicitly; instead, the literature mainly focuses on practical guidance (e.g., what constitutes a good research question). Consequently, we searched for literature – including textbooks, book chapters, and journal articles – that provides guidance on how to successfully perform activities [A1]-[A3]. This search was conducted via Google Scholar using search strings such as "good research question" and "good research hypothesis". To identify the most suitable and relevant sources, we screened the search results from the first ten pages for each activity [A1]-[A3] and applied the following eligibility criteria: citation count (N>100), academic publisher or provider, demonstrated expertise of the authors, language (English or German), and relevance of content, taking into account different research disciplines.

Figure 2. Overview of the research design.



After selecting the relevant sources, we conducted a qualitative content analysis following an inductive approach (Kuckartz, 2019; see Fig. 2). In the first step, we identified relevant text passages related to the requirements and analysed them using the chat function of the AI Assist in MAXQDA (version 24.11.0), the posed questions for this analysis are listed in Tab. 2. The AI Assist is designed to support users in identifying patterns within documents (e.g., desirable and undesirable characteristics associated with activities [A1]-[A3]) and is therefore suitable for facilitating the initial phase of text analysis (Kuckartz, 2019). The results emerging from this initial analysis were then summarised across all documents and further analysed using an AI chatbot (u:ai chatbot GPT-4o – University of Vienna) with the following prompt: "Please summarise the results from these three lists in the form of qualitative content analysis and inductive category development" (see Tab. 2). The resulting summaries were subsequently compared, leading to the development of a preliminary category system, which was then applied to the data and iteratively refined and expanded (see Fig. 2).

The challenges identified by Kranz et al. (2023) were formulated from a student-centred and predominantly deficit-oriented perspective, i.e., what students are not able to do. To adopt a more systemic perspective, these challenges were reformulated in an object-oriented manner (Abels, 2026). For this purpose, AI was used as a supportive tool for rephrasing (see Tab. 2), enabling multiple reformulations to be generated simultaneously.

Table 2. Overview of AI application for data analysis.

Aspect	Purpose of application	AI tool	Prompt
Requirements	Initial text analysis	MaxQDA 24.11.0 with AI Assist	"Please answer the following questions by presenting the answers in numbered lists: What are the requirements for a good [A1-A3]? What should one obey when [A1-A3]? What are features of a bad [A1-A3]? What should one avoid when [A1-A3]?"
	Creating inductive categories	u:ai ChatbotGPT 4o (University of Vienna)	"Please summarise the results from these three lists in the form of qualitative content analysis and inductive category development."
Challenges	Object-oriented rephrasing	Model: Meta Llama 3.1 8B Instruct, temperature: 0, top_p: 0.05	"Rewrite the following sentence making clear that the requirement comes from the subject itself and not from the students. Please note that the tone is academic, is scientific in nature, and that the sentence is rephrased in such a way that it is easy to understand and informative. Give me a list which is numbered like the original sentence. The original sentence is. …"

The results of the analyses of requirements and challenges were finally related to each other and reinterpreted as object-related barriers (see Fig. 2).

Results & Discussion

Due to the large scope and high complexity of the results, we will present, explain, and discuss one key result for each of the activities [A1-A3]. Tab. 3 provides an overview.

Table 3. Overview of selected results.

Activity	**Category & Subcategory**	**Source material** (paraphrased and summarised)	**Object-related barrier**
[A1] generating the research question	**Category**: Feasibility & Practicality **Subcategory**: Empirical testability	**Requirement** Research questions should be answerable through systematic observation, measurement, or data collection.	Research questions that aim to identify causal relationships between variables often require a specific type of inquiry, one that is empirically testable and grounded in the subject matter. In some cases, questions may be more descriptive or factual, rather than causal, which can limit the scope of investigation and the potential for meaningful conclusions.
		Challenge Students do not state causal research questions, but factual type questions which are not empirically testable.	
[A2] formulating a theory-driven assumption or hypothesis	**Category**: Consistency & Integrity **Subcategory**: A-priori Statement & Immutability	**Requirement** The hypothesis should be formulated before the research begins and must not be adjusted or changed throughout it.	The iterative nature of the scientific process often requires revisiting and refining hypotheses as new information becomes available. However, the modification of hypotheses without thoroughly testing can compromise the validity of the conclusions drawn.
		Challenge Students change their hypotheses during the process without having tested them first.	
[A3] planning an appropriate investigation	**Category**: Experimental Design & Control **Subcategory**: Test and Control Approaches	**Requirement** Experimental designs should include test and control approaches (qualitative design) or a series of measurements (quantitative design).	The investigation of complex phenomena requires consideration of multiple factors, including control of variables and the conduct of test and control trials. However, many experiments in school or everyday life lack these fundamental aspects, which can compromise the accuracy of the results.
		Challenge Many students experiment without a test or control trial and neglect the control of variables strategy (CVS).	

[A1] Generating The Research Question

The results indicate that one fundamental requirement for oIBL is the formulation of research questions that are empirically answerable and allow for systematic observation, measurement, or data collection. One typical form of such questions addresses relationships between variables, what provides a clear basis for selecting appropriate methods of investigation. In practice, however, a key challenge arises because students often tend to formulate descriptive or factual questions rather than causal research questions. These questions may focus on identifying or describing phenomena but do not readily support empirical testing or systematic inquiry. But instead of attributing students, we take a systemic perspective, which leads to an object-related barrier located in the research question itself: When research questions are oriented toward causal relationships, they constrain the type of inquiry that can be conducted (especially regarding methodological requirements) as there is a necessity of empirical testability, being anchored in subject-matter knowledge. However, research questions that students find interesting (or in different science disciplines) may also be more exploratory or descriptive in nature. This can limit the scope of investigation and reduce the potential for producing explanatory insights and meaningful conclusions. When teachers and teacher educators know about these object-related barriers, they can think of ways to enable participation in oIBL.

[A2] Formulating A Theory-Driven Assumption Or Hypothesis

One crucial requirement of activity A2 is the formulation of a hypothesis prior to the start of the investigation, with the expectation that this hypothesis remains unchanged throughout the research process. In this way, the hypothesis serves as a stable epistemic reference that guides the design of the study, the selection of methods, and the interpretation of the collected data. However, several studies found that students frequently revise or replace their hypotheses during the inquiry process without having systematically tested the original ones. Such modifications are often driven by emerging observations, unexpected results, or uncertainties during data collection and analysis. If we take a more systemic view, we can derive a barrier regarding the coherence between hypothesis, methodological approach, and empirical evidence. When hypotheses are altered without prior empirical testing, their role as structuring and validating objects of inquiry is weakened and results are limited in reliability, transparency, and explanatory power of arguments. Teachers and teacher educators who know that phrasing hypotheses is really difficult, can prepare scaffolds in advance to support students' science learning.

[A3] Planning An Appropriate Investigation

The findings show that one fundamental requirement for planning investigations [A3] is the implementation of well-structured designs that allow systematic approaches. In qualitative experiments, this entails the inclusion of test and control approaches, while in quantitative studies, it involves conducting a series of measurements that enable reliable observation of changes in variables. These strategies are essential for ensuring that differences in outcomes can be attributed to specific factors rather than uncontrolled influences. However, empirical results show that students often fail to adhere to this systematic approach. Several challenges arise because many students carry out experiments without including test or control trials and frequently neglect the control of variables strategy (CVS). As a result, multiple factors may vary simultaneously, making it difficult to determine which factor is responsible for the observed effects. Relating requirements and challenges to each other, the following barrier can be derived: When experiments are not carefully structured to control variables and provide appropriate comparisons, the investigation of complex phenomena becomes limited. Such designs compromise the accuracy, reliability, and interpretability of results, reducing the potential for drawing valid, meaningful, and generalizable conclusions from the inquiry process. Teachers and teacher educators can inform their students about these barriers and work on them instead of seeing students as the ones who fail the challenges.

Discussion

A key insight from the scoping review is that the requirements for individual activities [A1]-[A3] are often highly specific to particular disciplines, even within the natural sciences (e.g., biology vs. chemistry). Explanations frequently reflect a form of tacit, community-specific knowledge that is either imprecisely stated (e.g., the research question should be 'investigable') or not explicitly articulated at all. For instance, guidance often refers to 'relevant questions' or questions that 'contribute to the field' of research without providing concrete criteria. Additionally, the literature provides little clarity on when activities [A1]-[A3] should be considered 'successful'. This creates a significant challenge in educational contexts, particularly in science education at the school level, where uncertainty and high difficulty are prevalent. Part of this difficulty arises from scientific requirements being transferred into school contexts (e.g., the application of the Control-of-Variables Strategy (CVS) in elementary schools; Chen & Klahr, 1999). Addressing these aspects requires well-prepared and knowledgeable teachers, effective scaffolding within oIBL, and an appropriate attitude toward the inquiry process and inclusion.

Moreover, the literature highlights the importance of a perspective shift for successful inquiry, although most reported challenges are person-related and deficit-oriented, as shown in Tab. 1 (Baur, 2023; Kranz et al., 2023). Focusing on the identification and categorisation of barriers in the inquiry process (adapted from Krönig, 2015) reveals that relatively few challenges need to be located in the "Self" domain (barriers that are caused in the persons themselves), whereas the majority emerges from the subject matter itself. This indicates that many barriers are not caused by students' lack of skill or experience but are inherent to the structure of activities [A1]-[A3]. Consequently, a more systematic and accurate approach to barrier localisation requires reformulating student-centred barriers into object-related barriers, as illustrated in Tab. 3. This shift in perspectives could also help teachers to stop being constantly overwhelmed by oIBL because they focus on their students' lack of knowledge and skills and instead become capable of addressing these barriers – as strived for in the project *PlanFoL*.

Summary And Outlook

Across the analysed literature focusing on the requirements and students' challenges in the planning phase of oIBL, studies that explicitly address the numerous and diverse subject-related demands are rare. To enable a more accurate and systematic approach that both helps to identify barriers and supports students during their inquiry process – in the sense of an inclusive approach – it is necessary to reformulate and re-categorise students' challenges into object-related barriers. The process of reinterpreting barriers in this way is demanding, requiring extensive epistemic knowledge and expertise. One effective method for reframing students' challenges into object-related requirements is the use of AI.

The next steps involve finalising and validating the object-related barriers with experts and using the rephrased barriers to develop inclusive materials for the planning phase of oIBL. These materials will then be implemented, evaluated, and refined according to the observed barriers. Ultimately, the developed materials, along with guidance on their use, will be made freely available as Open Educational Resources (OER) under a CC-BY license on the platform *twillo*.

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ESERA 2025 Copenhagen

The Challenges Of Inclusive Science Education From Teachers' Perspectives

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International assessments, such as PISA, consistently show that many students in Germany and other countries lack key competencies, with a significant portion underperforming. Germany has also not fully implemented an inclusive school system in line with the UN Convention on the Rights of Persons with Disabilities, partly due to teachers' competencies in inclusion. Given these challenges, it is crucial to find ways to ensure all students can develop their competencies by enhancing teacher professional skills. This study investigates in-service teachers' perspectives on challenges in inclusive science teaching. By identifying competency requirements for teacher training that align with educational policies and inclusive practices, this research aims to enhance teacher preparedness for inclusive science education. Differentiating between subject-specific and general pedagogical challenges helps define targeted improvements in science teacher education. Using a qualitative-explorative methodology, guided interviews were conducted with 19 teachers to capture their experiences and perspectives. The findings reveal, for instance, challenges with learner prerequisites, individual competence development, selecting content and methods, enabling participation, using methods and media, as well as challenges related to experimentation and scientific language. This study highlights the urgent need for targeted teacher training programs that integrate both general pedagogical skills and subject-specific didactics, ensuring that science educators are better equipped to foster inclusive learning environments.

Keywords: inclusion, teachers, challenges

Introduction

International assessments like PISA show that many students lack scientific literacy, with a significant number underperforming (OECD, 2023). Additionally, the implementation of inclusive education remains insufficient (Klemm et al., 2023), partly due to teachers' competencies in inclusive pedagogy (Pit-ten Cate et al., 2018). Teachers play a crucial role in the success of inclusive education (Boer, 2012), and their professional skills significantly impact students' learning outcomes (Blömeke et al., 2022). However, teachers continue to face difficulties in fulfilling the additional requirements for inclusive science teaching (Pit-ten Cate et al., 2018). This study aims to explore these challenges and propose competency requirements for teacher training.

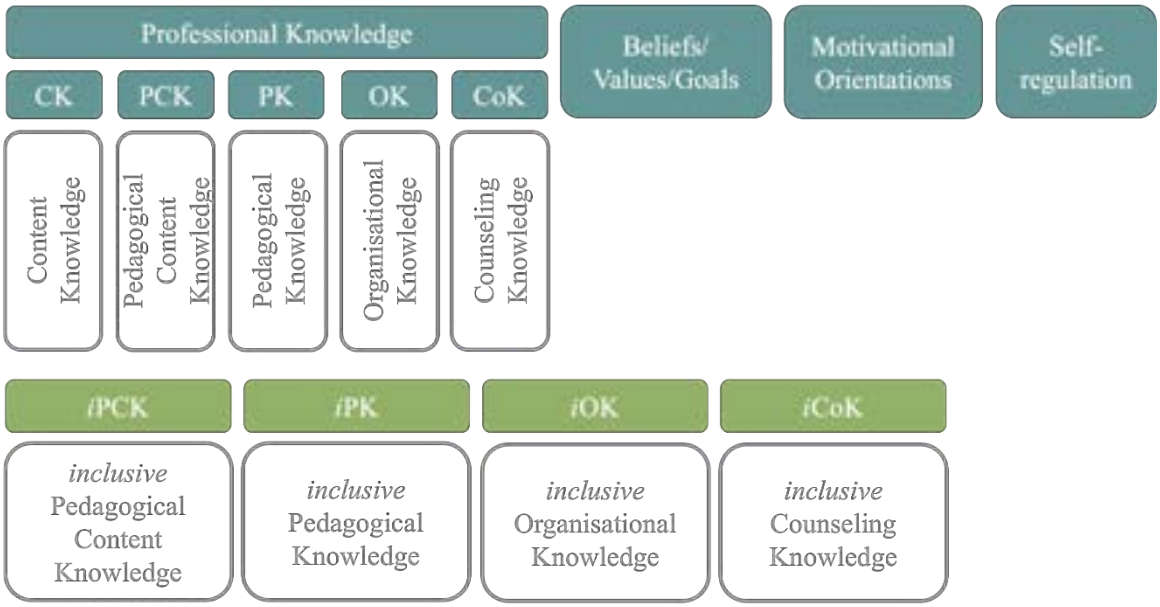
Theoretical Framework

Professional Competency Models

Despite policy efforts toward inclusion, teachers struggle to implement inclusive science teaching effectively (Moser & Lütje-Klose, 2016). Teaching expertise is shaped by knowledge, professional values, beliefs, motivation, and self-regulation skills (Baumert & Kunter, 2013). The competency model (see Figure 1) developed by Baumert and Kunter (2013) includes four aspects of professional competence: 1) Beliefs/Values/Goals, 2) Motivational Orientations, 3) Self-Regulation, and 4) Professional Knowledge. These aspects are further divided. Professional Knowledge is categorized into Content Knowledge (CK), Pedagogical Content Knowledge

(PCK), and Pedagogical Knowledge (PK), and expanded to include Organizational Knowledge and Counseling Knowledge (Baumert & Kunter, 2013).

Figure 1. Extended Competency Model for Inclusive Teaching Based on Baumert and Kunter (2013).



König et al. (2019) and Bertram et al. (2020) have expanded this model to include competencies specific to inclusive education. König et al. (2019) introduced inclusive general pedagogical knowledge (iPK) and inclusive organizational knowledge (iOK). Their review identified four key areas:

1. Diagnosis (assessment of support needs, initial and progress diagnosis),
2. Intervention (methods for individualization and addressing student diversity),
3. Management and Organization (collaboration with colleagues and external partners), and
4. Counseling and Communication.

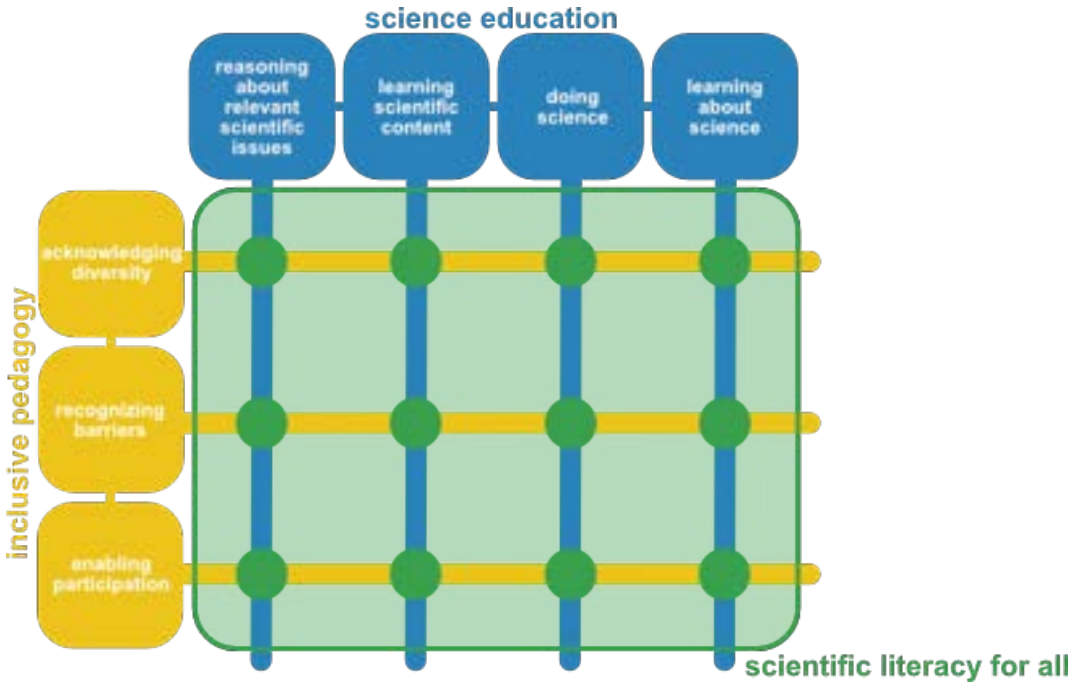
These areas were integrated into the competency domains: inclusive pedagogical content knowledge (iPCK), inclusive general pedagogical knowledge (iPK), inclusive organizational knowledge (iOK), and inclusive counselling knowledge (iCoK). Bertram et al. (2020) further refined the model, adding areas in iPCK (e.g. knowledge about learners' conceptions), iPK (e.g. methodological repertoire), iOK (e.g. school development processes), and additional areas in beliefs/values/goals, motivational orientations, and self-regulation.

The competency model for inclusive teaching (see Figure 1) (König et al., 2019, based on Baumert & Kunter, 2013) has been validated and was transformed into a category system (Bertram et al., 2020). For this study, the model and category system had to be adapted for (inclusive) science education.

NinU Framework

The NinU Framework (Stinken-Rösner et al., 2020) offers an initial theoretical orientation for adapting the competency model for inclusive teaching (see section before) to (inclusive) science education. This framework (see Figure 2) integrates inclusive pedagogical considerations with a scientific perspective in a unified model.

Figure 2. NinU Framework, Adapted from Stinken-Rösner et al. (2020).



The vertical axis of the NinU Framework emphasizes firstly the acknowledgment of student diversity. Teachers recognize the potential and resources of each student and incorporate these into their lesson planning (Booth & Ainscow, 2016). In a second step, the framework recognizes potential barriers, that can exist in teaching materials, classroom conditions, or even in the behaviour of the teachers themselves (Stinken-Rösner et al., 2020). Lastly, the framework's goal is adapting teaching methods accordingly to enable the participation of all students.

The horizontal dimension of the NinU Framework addresses the goals of science education, following Hodson (2014), including reasoning about scientific issues, learning science content in the sense of a conceptual understanding (Taber, 2013), doing science (engaging with scientific methods and procedures), learning about science (understanding the processes of science itself; Millar, 2006), and the use of digital media for accessibility (Abels & Stinken-Rösner, 2022).

State of Research and Research Questions

Although the competency model for inclusive teaching (based on Baumert & Kunter (2013) and expanded by König et al. (2019) and Bertram et al. (2020)) offers a strong starting point, it does not sufficiently capture the subject-specific demands of inclusive science instruction. Furthermore, the second dimension of the NinU Framework, "Recognizing Barriers", is currently addressed primarily through individual studies.

Overall, the field still lacks a shared definition of inclusive science teaching, and subject-specific criteria for required affordances remain underspecified. Some authors have outlined characteristics of individual scientific disciplines that might provide insights into their specific affordances (Hoffmann & Menthe, 2015). However, a coherent normative catalogue of subject-specific affordances is still missing. Therefore, the aim of this study is to explore the specific challenges teachers face in inclusive science lessons to define key competencies for teacher education. The research questions include:

- What general pedagogical challenges impact inclusive science teaching?
- What subject-specific challenges do teachers face in inclusive science lessons?

Research Method And Design

A qualitative-explorative research approach was adopted to capture teachers' perspectives on the challenges of inclusive science teaching. We conducted semi-structured interviews (Helfferich, 2014) to balance openness to participants' experiences with the possibility of targeted follow-up questions (Kuckartz & Rädiker, 2022).

The interview questions were developed based on the NinU framework, emphasizing barriers to inclusive education (Ferreira González et al., 2021; Stinken-Rösner et al., 2020). The term 'barrier' was replaced with 'challenge' to reduce associations. The interview guide began with the question: "When you think about the planning, implementation and reflection of your [science/physics/biology/chemistry] lessons, what were and are challenges for you?" (see Figure 3), allowing respondents to highlight specific concerns regarding inclusive science education. The respondents' understanding of inclusion is implicitly explored in the further course of the interview.

Figure 3. Excerpt from the Interview Guide with the First Question.



The study focused on in-service teachers in northern Germany, with a total of 19 structured interviews analysed. The teachers were recruited through a network-based approach. Interviews were transcribed and analysed using qualitative content analysis (Mayring, 2022) resulting in the summarization of the interview's core statements into paraphrases. A coding guide was developed based on the competency model for inclusive teaching and the deductively identified categories. The paraphrased data was coded independently by two researchers, achieving an interrater reliability of Cohen's Kappa = .67. Discrepancies were resolved through consensus discussions, ensuring consistency in the categorization of responses.

Findings

The qualitative content analysis (Mayring, 2022) of the interviews yielded 275 codes. Overall, teachers' accounts clustered strongly around challenges that are intervention-oriented—i.e., challenges that arise when planning, enacting, and adapting instruction in inclusive science classrooms, with the largest clusters located in "Intervention iPK" (inclusive Pedagogical Knowledge on Intervention) with 122 codes and "Intervention iPCK" (inclusive Pedagogical Content Knowledge on Intervention) with 60 codes. 50 codes were assigned to the category "framework conditions", whereas 43 codes are dispersed across all remaining categories of the Extended Competency Model for Inclusive Teaching.

In the following, the challenges related to iPK and iPCK are discussed in more detail, with particular attention to "Intervention iPCK", as it is especially informative from a science education research perspective. For a comprehensive analysis and further insights into all categories, see Basten et al. (submitted).

General Pedagogical Challenges Impacting Inclusive Science Teaching

"Intervention iPK" includes general pedagogical knowledge. Inductively, challenges were grouped into the following subcategories:

Learner Prerequisites

Teachers frequently described the difficulty of addressing a wide spectrum of students' individual characteristics, prior knowledge and beliefs/conceptions about a topic.

> "The presence of diverse resources across multiple domains—such as pre-instructional experiences, values, prior knowledge, and reading and writing skills—can constitute a challenge both for the teacher and for the learner themselves." (HI-002; F15)

Individual Competence Development

A major challenge concerned supporting students' individual learning progress in a way that is feasible in everyday teaching. Teachers emphasized that "adequately support[ing] each student in the learning process according to their individual level of learning progress" requires continuous adaptation and individualized support structures.

> "It constitutes a challenge for the teacher to create a safe environment in which even introverted students feel confident to participate and verbalize their solutions." (2022-LG-011_F8)

Topics And Contents

Teachers often described challenges in preparing lessons that motivate students. In addition, didactic reduction was mentioned as demanding—particularly when adapting science content for students with special educational needs.

Participation

Many statements addressed the challenge of ensuring that all students—especially those with special educational needs—can participate in learning activities. Teachers reported "additional support efforts for students with special educational needs".

Methods And Media

Teachers highlighted the challenge of identifying working methods and materials that meet diverse needs while remaining inclusive (and not excluding students with special educational needs).

> "Taking into account individual support needs and the accompanying necessity for instructional adaptations (for visual impairment: larger illustrations, magnifying glasses for reading texts, etc.; for learning difficulties: texts in simplified language, temporal adjustments) constitutes a challenge for teachers." (LFG; HI-002; F17)

Communication

In the last subcategory, some teachers reported challenges in adapting to heterogeneous language needs in science lessons. One example concerned dealing with language accuracy during learning processes, such as the perceived difficulty of "correcting language errors immediately".

Subject-Specific Challenges In Inclusive Science Lessons

"Intervention iPCK" focuses on pedagogical content knowledge specific to science teaching. Here, teachers' statements concentrated on three inductively formed subcategories:

Experiments

Experiments emerged as a key challenge in inclusive science teaching. Teachers referred to difficulties across preparation, implementation, and follow-up, mainly regarding time and materials. They reported that extensive preparation and set-up time competes with time needed for in-class support, and that clean-up/follow-up often cannot be completed immediately due to everyday time pressure. The prevailing 45-minute lesson rhythm was described as incompatible with longer inquiry cycles, including experimentation and consolidation phases.

Beyond time constraints, teachers highlighted material and organizational demands, such as compiling experimental materials for an entire class and selecting experiments that fit both the topic and the learners' age and needs. Teachers also emphasized the inherent unpredictability of experimental outcomes and the dependence on external conditions, which complicates planning and inclusive scaffolding.

From an inclusion perspective, experimentation was described as requiring continuous adaptation to heterogeneous learner prerequisites, including different competence levels and, in some cases, limited experimentation skills on the learners' side. Teachers additionally reported challenges in classroom management during experiments (e.g., increased noise and unrest, especially in younger classes) and in finding a productive balance between allowing exploration and providing sufficient guidance.

Finally, several paraphrases pointed to safety and specific support needs: teachers described the difficulty of keeping all students in view during potentially dangerous experiments, enabling participation of students with disabilities (including autism spectrum conditions), and supporting anxious students during hands-on activities.

> "Including students with autism spectrum disorder in experimental lessons constitutes a challenge." (2022-LG-016_F10)
>
> "Keeping all students in view during dangerous experiments constitutes a challenge." (2022-LG-016_F4)
>
> "Designing experiments in a way that allows students with disabilities to participate." (2022-LG-10b)
>
> "A restless learning group constitutes a challenge during experiments." (2022-LG-012_F2)
>
> "Finding a group composition favorable for all learners during experiments constitutes a challenge." (2022-LG-012_F2)

Scientific Language And Scientific Methods

Teachers described scientific language as a major challenge, especially for students with German as a second language, where "technical language may make it difficult […] to understand the content". At the same time, teachers framed this as a tension: they need to respond to learners' linguistic prerequisites while also promoting the development and active use of scientific terminology. Paraphrases also indicated that the distinction between everyday language and scientific language remains challenging even in higher grades, requiring repeated and systematic language work. In addition, teachers associated subject-specific accessibility with reading and

text difficulty: due to low reading levels textbooks in primary science are perceived as too complex.

> "The teacher faces the challenge of enabling students to master and use subject-specific language." (2022-LG-011_F7)

> "In summary: the low reading level of students constitutes a challenge, as the texts in elementary science textbooks are often too difficult." (2022-LG-008_F2)

Beyond language, teachers also reported challenges related to scientific methods, for instance scaffolding inquiry processes and helping students approach a research question, raising the issue of how to prepare students for inquiry-oriented phases.

> "The prerequisites of students for guiding them toward the research question vary in heterogeneous classrooms." (2022-LG-009-F001)

Presenting Information

Another subject-specific challenge concerned the appropriate presentation of information, including responding to students' misconceptions and missing foundational prerequisites. Teachers noted situations in which students lack key conceptual foundations (e.g., "when children have no concept of quantities"), which makes it difficult to introduce or build scientific explanations without extensive preparatory conceptual work. Closely connected, teachers described didactic reduction and student-friendly representations as demanding, especially the need to simplify without introducing inaccuracies, which was perceived as particularly challenging in physics and chemistry.

> "Didactic reduction—simplifying without making errors—constitutes a challenge for the teacher; this is more pronounced in physics and chemistry than in biology." (2022-LG-008_F1)

> "Student-appropriate presentation constitutes a challenge for the teacher; this challenge is greater in physics and chemistry than in biology." (2022-LG-008_F1)

> "Demonstrating the relevance of the subject to students through everyday and societal topics (such as climate change, the environment, ecosystems)." (2022-LG-13-F004)

Additional iPCK-Related Challenges (Emerging Themes)

Beyond the three main clusters, some paraphrases pointed to further subject-specific inclusive demands: handling sensitive topics such as evolution and sexuality education in relation to students' religious/worldview backgrounds; conveying the societal relevance of science topics; teaching interdisciplinary science formats; and implementing short excursions or out-of-school learning activities.

> "Topics such as evolution and sex education pose a challenge for teachers and students, as they are not necessarily compatible with religious beliefs or worldviews." (LFG; HI-002; F13)

> "Planning and alignment of out-of-school learning sites relevant to the science domain (e.g., weather) constitutes a challenge." (2022-LG-005-F003)

Overall, the iPCK paraphrases depict inclusive science teaching as highly dependent on teachers' capacity to design and manage resource-intensive science practices (especially experimentation and inquiry) while simultaneously ensuring linguistic accessibility, conceptual scaffolding, and safe participation for all learners.

Discussion And Implications

Overall, the findings indicate that many teachers feel insufficiently prepared with regard to both general pedagogical and subject-specific didactic skills necessary for effectively implementing inclusive education in science classrooms. The prominence of intervention-related challenges suggests that teachers particularly struggle with translating inclusive aims into concrete classroom practices (e.g., differentiation, participation, scaffolding experiments and inquiry, and language-sensitive science teaching). Accordingly, the results point to a need for targeted professional development that strengthens these specific, practice-oriented competencies.

More than fifteen years after the UN-CRPD, its implementation in schools remains inadequate. Recent monitoring reports suggest that political and societal commitment to inclusive education is currently weakening (Lepper & Steinmann, 2024). At the same time, teachers report substantial workload and pressure, which are associated with frustration and an increased risk of burnout. Against this backdrop, it appears particularly urgent to systematically identify the concrete challenges teachers face and to address them through coherent support structures. Our findings suggest that one major gap concerns knowledge and skills related to concrete lesson design in inclusive science classrooms. Consequently, initial teacher education (including university-based coursework) should place greater emphasis on evidence-informed, feasible instructional approaches and resources that enable teachers to plan and enact inclusive science lessons under real-world constraints.

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Youth's Environmental Attitudes And Use Of Digital Media And Social Networks: A Comparative Exploration From Seven Spanish-Speaking Countries

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This study presents an international comparison among seven Spanish-speaking countries on the two main themes of the ESERA-2025 conference: the environmental attitudes (EAs) and the use of digital media and social networks (DM). Both categories are quantitatively and qualitatively assessed from the voices of a large sample of 15-year-old students from seven Spanish-speaking countries. The students answered the questionnaire of an international project (The relevance of science education second, ROSES) that explores some attitudes and experiences of science education. Further, gender and cross-country differences are also checked through the probability of signification and the effect size of the differences. The main overall findings point to students' proactive EAs and moderate DM use in science classes that are also quite parallel across countries, though Argentina and Mexico tend to display more polarized scores on EAs and DM use. Another finding shows generalized gender differences about EAs and DM use across countries. Girls tend to hold more positive EAs than boys across all countries, though their effect size ranges from moderate to small differences. Regarding DM use, boys reported higher overall DM use than girls, though the gender effect sizes are insignificant. The consequences of these results for science education and for research on these issues, the limitations of this study, and the future prospective are discussed.

Keywords: environmental attitudes, digital media, gender differences

Introduction

This study explores an international comparison on the two themes of the ESERA-2025 conference through assessing the environmental attitudes (EAs) and the use of digital media and social networks (DM), as reported by young people from seven Spanish-speaking countries. Further, international comparisons constitute an additional instrument of educational research that contributes contexts to absolute evaluation measurements, thus lending a value-added meaning, thanks to the comparisons between the different contexts (e.g., OECD, 2025). These features frame the relevance and the methodological foundations of this study to science education research and practice.

For decades, the study of attitudes has been a fruitful area of social psychology because attitudes, in addition to their evaluative component (acceptance/rejection), further act as guides to behaviour (e.g., sustainable actions or digital use). Thus, the dispositions (acceptance/rejection) toward the environment, or EAs, guide environmentally sustainable conduct, which also has a long history within science education. Pro-environmental conducts have been gaining research and educational relevance on the global agenda due to the growing impact and social emergency of the increasing environmental deterioration, such as climate change. The UN declared the Decade of Education for Sustainable Development (2005-2014) and then the 2030 Agenda (UN, 2015), which sets out 17 priority Sustainable Development Goals for guiding governments and citizens' actions until 2030, which represent a global challenge for education. Understanding EAs

is crucial for developing strategies for sustainable development through targeted and effective messaging.

The literature on conceptualizing and defining EAs is large and complex to show consensus. Above all, EAs are attitudes and share with general attitudes the same theoretical base, which involves cognitions (beliefs), affects (acceptance/rejection), and behaviours (actions). A current significant consensus acknowledges that EAs involve a single overall attitude to the environment but hold a multi-dimensional structure that organizes a range of environmental topics. However, the field is fragmented by disagreements that include the number of EA dimensions and the nature of the EA specific topics. Thus, some unified definition and conceptualization of EA, the measurement methodology, and even the evaluation survey are highly pursued (Somerwill & Wehn, 2022).

The Environmental Attitudes Inventory (EAI) provides a theoretical reference framework and a comprehensive method of the material currently available in the field, because EAI has been used across a range of contexts and has been found to be highly consistent and reliable (Milfont & Duckitt, 2010). The EAI short form is made of 72 items across twelve first-order factors (dimensions), grouped into two second-order factors, Preservation (seven first-order factors) and Utilization (five first-order factors).

On the other hand, the educational importance of digital media and social networks (DM) arises from the effectiveness and impact of their implementation in the various contexts of education, due to their advantages for the pedagogy, the DM literacy and the skills, and, in general, the relevance of digital learning for science education. Further, the endless risks and drawbacks of digital misuse need to be recognized, addressed, and overcome in science education (Tibaná-Herrera et al., 2018). In particular, a good attitude towards DM, trust in DM, and firm beliefs in their usefulness and their autonomous use had a positive relationship to students' academic performance in mathematics and science (Courtney et al., 2022). Further, similar results have been obtained for the overall digital development of a country and the use of DM at home by students (Skryabin et al., 2015).

Since the first studies, men have shown better attitudes to science than women, though the magnitude of the gender differences ranges from mild to moderate (Osborne et al., 2003; Potvin & Hasni, 2014). Regarding EA, the revision of Gyurián Nagy (2025) found that women exhibited higher EAs, greater awareness of environmental problems, and a higher willingness to change their behaviour to reduce their environmental impact. In contrast, men’s attitudes are more varied, reflecting a broader diversity of opinions.

Gender has not been a frequent variable in DM studies. For instance, the review by Momani et al. (2023) does not mention it. With respect to the opportunities offered by DM, social studies place women in an unfavourable position that displays three digital gaps: unequal access to infrastructures and digital tools, low level of digital skills, and Internet use (Sáinz et al., 2020). Thus, gender is important for DM too.

The international study “The Relevance of Science Education Second” (ROSES) listens to students’ voices and opinions on their EAs and on their use of digital media and social networks at home, school, and in the science classroom, as well as their perceptions of the DM quality for learning (Jidesjö et al., 2020).

The research questions about the exploration of young students’ EAs and DM use in seven Spanish-speaking countries are the following: How much do students hold proactive EAs and use general and specific DM in science classes? What are the main differences across countries about EAs and the DM use? What are the differences between boys and girls across countries?

Methodology

ROSES uses a mixed-method methodology, which involves qualitative and quantitative procedures to analyse the students' answers and to develop comparisons between groups.

Materials

The ROSES-Q is a large survey that was developed by an international team of science education experts to gather diverse affective data that impact science education (Jidesjö et al., 2020). The item wording is direct, simple, and short, and the students are asked to tick the appropriate box number that best fits their attitudes through a four-point Likert format (1-2-3-4). The meaning of the Likert numbers varies across scales (Disagree-Agree, Never-Often, etc.).

The categories about EA challenges and the use of DM at home and school science are analysed here. The category "Me and the environmental challenges" displays 13 items on the personal dispositions towards the environment, asking How much do you agree with the item? All responses are expressed on a four-point Likert scale (1-4), whose extreme points spread from disagree (1) to agree (4).

Six EA items are marked with (-) because they display anti-EAs (e.g., Threats to the environment are not my business), as they are contrary to pro-EA (e.g., People should care more about how to protect the environment). The average scores of the dysfunctional negative items should be interpreted in an opposite way to pro-environmental items. The EAs items correspond with the following dimensions of the short EAI: (2) Support for interventionist conservation policies, (3) Environmental movement activism, (4) Conservation motivated by anthropocentric concern, (5) Confidence in science and technology, (6) Environmental fragility, (8) Personal conservation behaviour, and (11) Ecocentric concern (Milfont & Duckitt, 2010).

The category "Use of digital media and social networks" is made up of 16 statements, which investigate digital experiences from three different perspectives: the time of DM use at school and at home (first 2 items), the use of several digital resources in school science education (10 items), and the appreciation of the quality of DM for learning science (last 4 items). Students were asked in the first two perspectives, "How much do I use the DM?" and in the third perspective, "To what extent do you agree with the following statements?" The responses are expressed on a four-point Likert scale (1-4), whose extreme points are as follows: first perspective, less than 2 hours a day (1) to more than 6 hours a day (4); second, never (1) to often (4); third, disagree (1) to agree (4) (Figure 1).

Participants

The target population of ROSES is 15-year-old students, because they are about to end compulsory education can look back to their school science education and reflect on what they have learned. The participants in this study validly answered the ROSES-Q in Spain (6014), Colombia (1279), Uruguay (729), Chile (729), Peru (470), Argentina (232), and México (191). The country samples are approximately split in halves between girls and boys.

The approval of the ROSES project by the Spanish State Research Agency implied the commitment to comply with the ethical principles and the relevant national, European, and international legislation on human rights. Students were informed that answering meant consent to participate, they could leave items unanswered, and the survey was anonymous.

Procedures

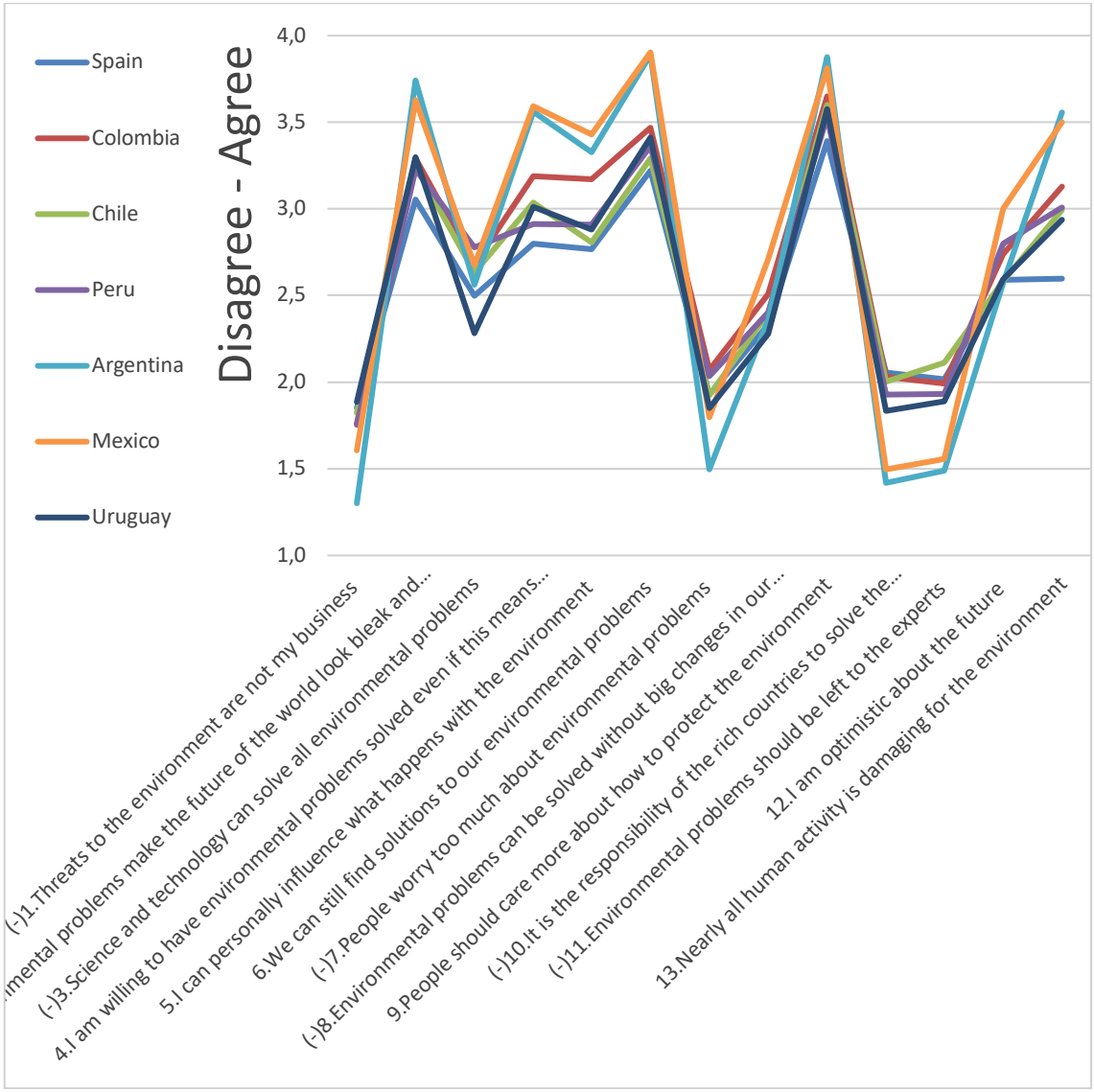
The data gathering took place from 2021 to 2024, and students anonymously and digitally answered the ROSES-Q as a class assignment led and collected by their teachers at each participating school.

The analysis summarizes the four percentages of each item within one single parameter, the item weighted average. The effect size (ES) of the differences (measurement of differences in normalized scores) allows analysis of the magnitude of the differences (low, medium, or large) that go beyond the statistical significance probability test ($p < .05$). Parametric (Cohen *d*) and non-parametric (Cohen *r*) ES tests were computed and interpreted this way: very small (< .10), small (< .30), moderate (< .50), large (> .50), and very large (> .80). ES scores of gender differences are computed as girls minus boys, so that positive differences represent higher scores of women.

Results

The main global qualitative feature exhibited by the EAs item averages of the seven countries shows that the countries' profiles are quite parallel among them. All country lines display their maximum and minimum scores on the same items with some minor exceptions (Figure 1).

Figure 1. Weighted average of environmental items for the seven countries.



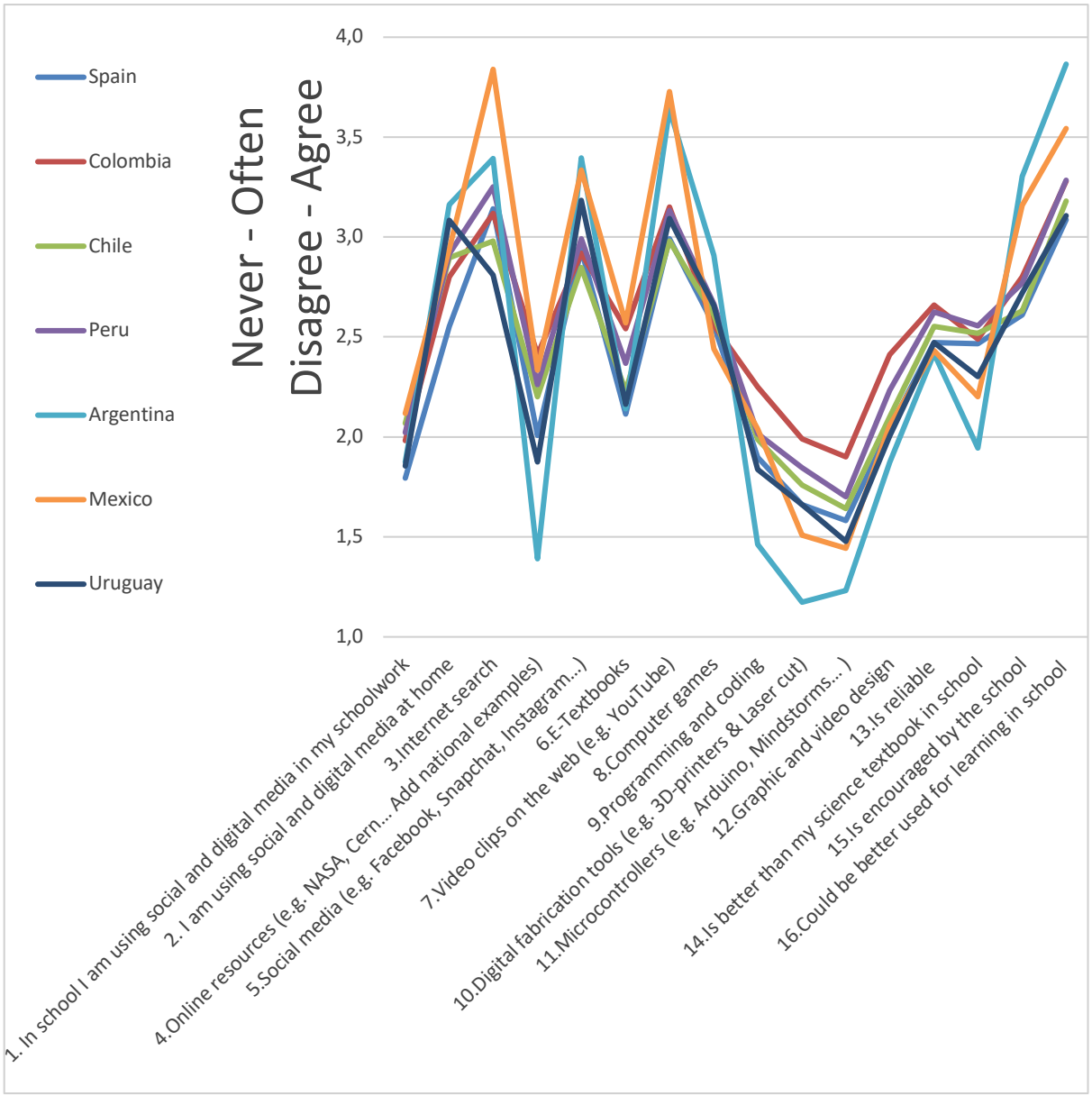
The items with the highest scores (large agreement) are three positive items: item 2 ("Environmental problems make a hopeless future"), item 6 ("We can still find solutions to

environmental problems"), and item 9 ("People should worry more about environmental problems"). Similarly, the points with the lowest scores (large disagreement) correspond to item 1 ("Threats to the environment are not my business"), item 7 ("People worry too much about environmental problems"), item 10 ("The responsibility lies with rich countries"), and item 11 ("Environmental problems should be left to the experts") (all three negative items).

On the other hand, the comparison among countries shows that most EAs items display large differences, which approximately score over one unit of the Likert scale between the country with the highest and lowest score (this difference corresponds to one standard deviation ES). The lowest differences between countries (under one unit of the Likert scale) correspond to item 3 ("science and technology can solve all environmental problems"), item 8 ("problems can be solved without major changes in our way of life"), and item 12 ("optimistic about the future").

The profiles of the seven countries along the 16 DM item averages are quite parallel. All country lines display their maximum and minimum scores on the same items with some minor exceptions, which is their main global feature (Figure 2).

Figure 2. Weighted average of digital media items for the seven countries.



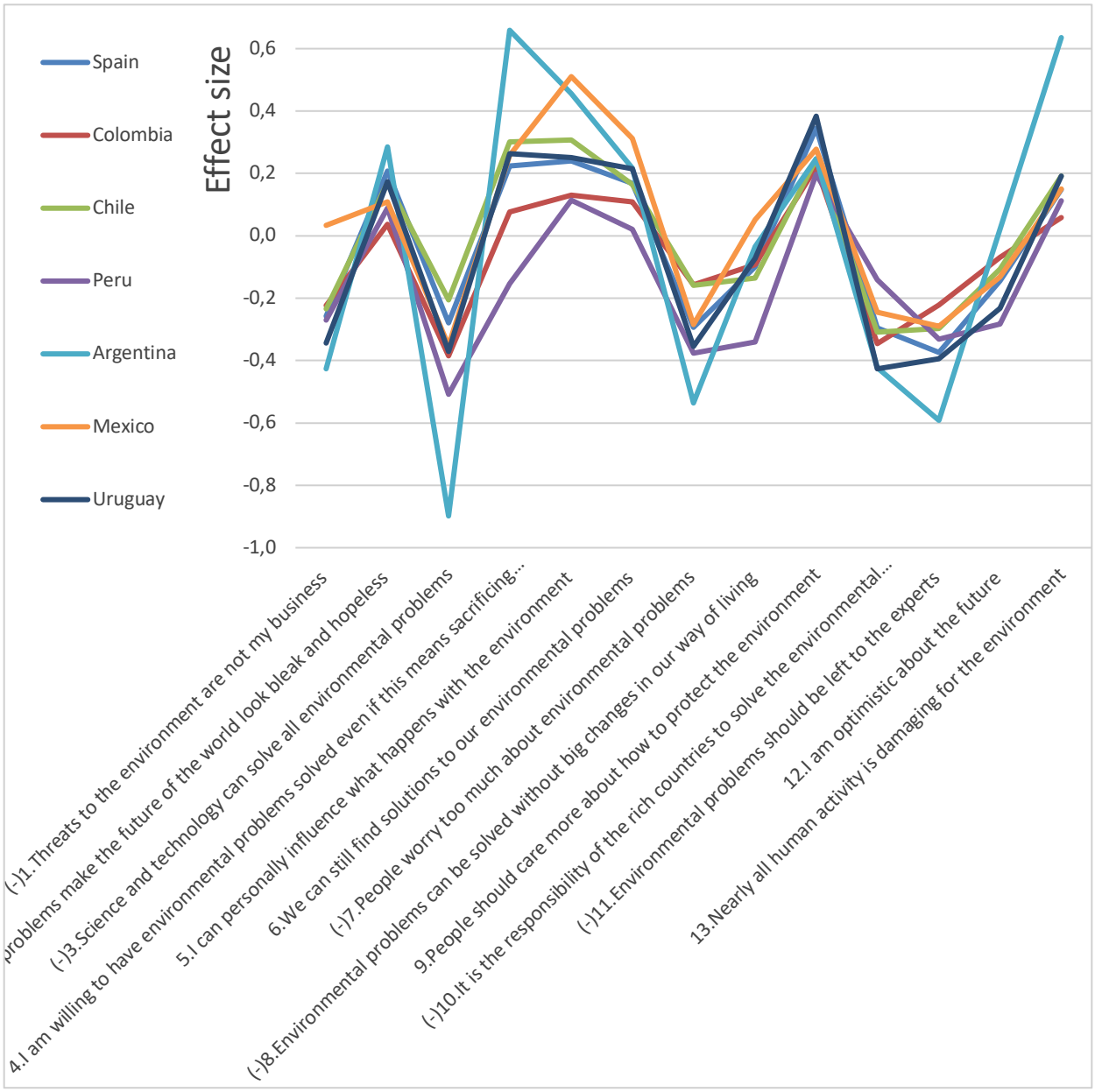
The items that reach the highest scores (largest use) are 2 ("use of social and digital media at home") and item 7 ("Video clips on the web"), and there is large agreement on item 16 ("DM

could be better used for learning in school"). Similarly, the items with the lowest scores (scarcest use) correspond to items 1 ("use of social and digital media at school"), 4 ("Online resources"), 9 ("Programming and coding"), 10 ("Digital fabrication tools"), and 11 ("Microcontrollers").

Further, Figure 2 also shows that almost all DM items display large differences between the highest- and lowest-score countries that are approximately higher than one unit of the Likert scale (over one standard deviation). The lowest differences between countries (under one unit of the Likert scale) correspond just to item 1 ("use of social and digital media at school").

Globally, Argentina's and Mexico's EAs stand out for being more positive than the rest of the countries. Their averages are well above the other countries in the positive items, and they are well below the other countries in the negative items. This result is also observed in the use of DM in science education: Mexico and Argentina tend to score lower than the other countries in the lowest-score items and tend to score higher in the highest-score items.

Figure 3. Effect size of gender differences on environmental items for the seven countries.



Gender differences

Gender differences in EAs and DM use have been assessed using parametric and non-parametric methods for computing statistical significance and effect size. Most items show significant gender

differences ($p < .05$) through parametric and non-parametric tests, even for low effect sizes (< .10). For this reason, the following analysis focuses on effect size statistics that are much more demanding and relevant for practice than the simple hypothesis testing statistics (probability of significance test). Parametric (Cohen *d*) and non-parametric (Cohen *r*) effect size statistics have been compared for EAs and DM use. Both effect size statistics produce highly coincident results, so that Cohen *d* has been selected (Figures 3 and 4).

The EAs (Figure 3) show that many items in many countries do not exceed the threshold of the effect size magnitude corresponding to small differences (-.20 - +.20). However, some items stand out of this interval with moderate to large differences. The items with positive differences (favourable to women) correspond to items 4 ("I am willing to have environmental problems solved even if this means sacrificing many goods"), 5 ("I can personally influence what happens with the environment"), and 9 ("People should care more about how to protect the environment"). These results mean that women agree more than men with the EAs represented in these items. As all these items display a positive formulation (pro-environmental), women hold better EAs than men, and the effect size of the gender differences is moderate to large.

The items with negative and moderate to large gender differences (favourable to men) are item 1 ("Threats to the environment are not my business"), 3 ("Science and technology can solve all environmental problems"), 7 ("People worry too much about environmental problems"), and 8 ("Environmental problems can be solved without big changes in our way of living"). Thus, men agree more than women with the negative (anti-environmental) attitudes represented in these items. The negative (anti-environmental) content of the former items requires a reversed interpretation of their scores, which means that women hold better attitudes than men on these items.

After reversing the scores of the anti-environmental items, the global differences on EAs show that girls have more positive attitudes than boys across all countries, and the effect size of the differences is noteworthy in the EA items mentioned above.

The overall effect size of gender differences on EA items approaches a positive moderate effect size, approximately .20. Exceptionally, Argentina exhibits a higher overall effect size of gender differences (over .40) that nearly reaches significant differences in effect size. This means that Argentine girls stand out for having the highest magnitude of the gender differences in comparison to the rest of the countries. Argentinian girls have much better attitudes than Argentinian boys, and just double the gender differences of other countries on EAs.

Argentinians' averages in the negative items are well below the other countries, yet they are well above the other countries in some positive items. Thus, Argentinian girls display much better EAs than Argentinian boys and double their gender differences in comparison to the other countries. According to this trend, some outlier effect size scores are noteworthy. Argentina scores much higher than the other countries in the positive items 4 ("I am willing to have environmental problems solved even if this means sacrificing many goods") and 13 ("Nearly all human activity is damaging for the environment"). Further, Mexico scores well over the other countries and against the former trend in the negative item 1 ("Threats to the environment are not my business").

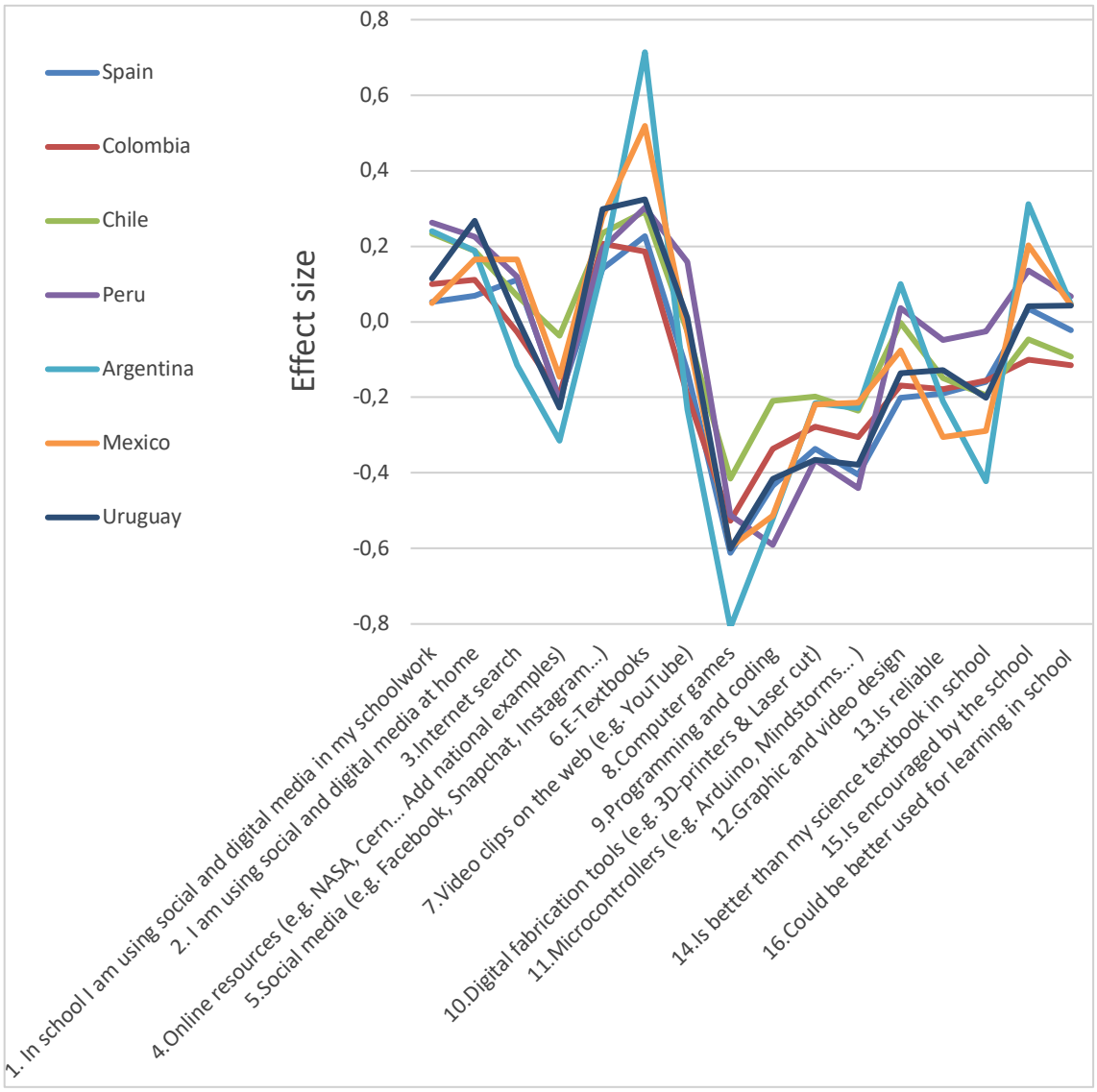
The gender differences in DM use (Figure 4) show that many items in many countries fall well below the threshold of the effect size magnitude, which corresponds to small differences (-.20 to +.20). However, some items stand out of this interval, showing moderate or large differences. The items with moderate or large positive differences favourable to women (positive) correspond to items 5 ("Social media") and 6 ("E-Textbooks"), which means that women report greater use

than men with these DM. Thus, women hold better DM use than men along these two items with moderate to large positive effect sizes of gender differences.

The items on the DM use that reach an overall moderate to large negative gender difference (favourable to men) correspond to items 8 ("Computer games"), 9 ("Programming and coding"), and 10 ("Digital fabrication tools"). Men use more than women the resources depicted in these DM items. Overall, these results allow us to conclude that women and men widely differ between them in the use of the DM mentioned above, giving different patterns tied to gender.

Regarding overall gender differences on DM use, Argentina again stands out for having more extreme scores than the rest of the countries. The effect size average items are well below the other countries in the DM with negative effect size (Argentinian men do use these DM much more than men of the other countries do) and they are well above the other countries in some positive effect size items (Argentinian women do use these DM much more than women of the other countries do).

Figure 4. Effect size of gender differences on digital media use for the seven countries.



Regarding DM use, the global effect size scores of the gender differences are negative for all countries, indicating that boys report a higher DM use than girls. However, these negative scores correspond to very small gender effect sizes. It is worth noting that Argentina displays the highest range of the distribution of effect size across DM items compared to other countries, indicating

that Argentina shows the highest and lowest effect sizes of gender differences across some DM items.

Discussion And Conclusions

The findings of this study answer the research questions about the current EAs and DM use in school science education through surveying students in seven Spanish-speaking countries.

The first finding points to students' overall proactive EAs, as the weighted averages of all EA items are over the midpoint of the Likert scale (after reversing the scores of negative items). Further, the EA items that display the highest and lowest attitudinal strength have been identified (Somerwill & Wehn, 2022). Regarding DM use, the item weighted averages are quite varied, giving rise to the more and less used DM resources (Skryabin et al., 2015).

Second, the students' EAs and DM use in school profiles across the set of items exhibit overall similar qualitative patterns for countries. However, the quantitative comparison between countries within each item shows large differences among countries for most EAs and DM items. Then, the items that display the largest and smallest differences among countries have also been identified and displayed as findings of this study.

Third, the weighted averages of Argentina and (partially) Mexico play the role of outliers in relation to the weighted averages of the other countries; that is, Argentina and (partially) Mexico often score in the top or the bottom of each EA and DM use item. Taking into account the overall scores on EAs and DM use, the seven countries seem to fit the following tentative table league (from top to bottom weighted averages): Argentina, Uruguay, Spain, Chile, Mexico, Peru, and Colombia.

Fourth, the study found generalized gender differences about EAs and DM use and a notable variance among countries. The overall differences on EAs show girls displaying more positive attitudes than boys across all countries, and the effect size of the gender differences is noteworthy in some EA items that have also been identified. The exploration of countries shows that Argentina exhibits the highest effect size of EAs' gender differences, which means that Argentinian girls have much better attitudes than Argentinian boys. Further, the magnitude of the gender differences on EAs just duplicates the gender differences of other countries (Gyurián Nagy, 2025; Sáinz et al., 2020).

Regarding DM use, the global effect size scores of the gender differences are mostly negative for all countries, which means that boys overall report higher DM use than girls. However, these negative effect size scores correspond to insignificant gender differences. Further, these gender differences induce different patterns of DM use that are tied to gender: girls report much more frequent use of e-textbooks than boys, and the reverse pattern applies to computer games, where boys report much more frequent use than girls. Again, Argentina tends to display the highest and lowest effect size of gender differences across many DM items. Overall, these results lead us to conclude that women and men widely differ in DM use.

The findings about students' EAs and DM use project obvious consequences for practice. First, school science education should remedy the weaknesses of EAs and DM use, such as increasing the educational use of computer games or trying to change anti-environment attitudes of the minority of students. Further, research should deepen the analysis within each country and the contrasts between countries (Courtney et al., 2022; OECD, 2024).

The limitations of this study mainly stem from its dependency on the ROSES-Q instrument, as its specific design conditions the results. For instance, the EA items do not develop all the environmental dimensions of the EAI (Milfont & Duckitt, 2010), and the DM does not include

the impact of artificial intelligence. Further, the samples in some countries (Mexico and Argentina) are small and harm their representativeness.

The future of this study envisages practical applications and developments of all the findings presented above for school science education and for research in science education. Particularly, the weaknesses and strengths of EAs and DM use and their gender differences may need future confirmation through new studies with renewed samples and contexts in the different countries.

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Part 13 / Strand 13

Science Curriculum And Educational Policy

Co-editors: *Irene Drymiotou & Marta Romero Ariza*

Part 13 / Strand 13 Science Curriculum And Educational Policy

Science curricula development including design, adoption, and comparison, as well as reform implementation, dissemination, and evaluation. Includes evaluation systems and practices adopted and implemented in schools and institutions; and construction, interpretation, implementation, implication and reflection of policies and reforms at the local, regional, national, or international levels concerning science education.

Sub-themes:

1) STEM Curriculum for young learners (<7 years)
2) STEM Curriculum for primary level
3) STEM Curriculum for secondary level
4) International perspectives in STEM policy & curriculum
5) Evaluations systems and practices

Contents

Strand 13: Science Curriculum And Educational Policy.....1229

The Evolution Of Competence And Agency In Science Education: A Conceptual Analysis 1232

Ready for PISA 2025? A Comparative Analysis of Taiwan and Manitoba Science Curricula 1240

Dynamic Equilibrium In Science: Comparison Between The Israeli And United States Frameworks And Representations In The Standards And Textbooks.....1247

Can Climate Literacy be taught in Special Education in Greece? Possibilities offered by science textbooks in upper high schools 1254

The Science Curriculum as a Vehicle for Climate Change Education: A Cross-Country Project 1261

Strand 13: Science Curriculum And Educational Policy

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Introduction

We are living in a transformative era shaped by profound technological advances. While these developments offer fascinating opportunities, they also present major societal and environmental challenges. Science Education should be responsive to these societal and environmental challenges and refine its practices and purposes (White & Tytler, 2025).

Under the theme *Transitions in Science Education: Sustainability and Digital Advances*, this chapter explores how science education can best prepare future citizens to face such challenges. Within this context, the science curriculum plays a crucial role, given that educational systems remain heavily curriculum driven. By examining how science curricula and educational policies worldwide are being reshaped, we contribute to a broader scholarly dialogue on what it means to educate scientifically literate and globally competent citizens. The Science Curriculum and Educational Policy Strand within ESERA focuses on the design, development, interpretation, implementation and evaluation of science education policies across local, regional, national, and international levels, as well as critical reflections on their border implications for science education.

Aligned with the main topics presented at the ESERA 2025 Conference within this strand, this chapter offers eight selected works, three of which are presented together as part of an ESERA symposium paper. The contributions span a wide variety of geographical contexts, displaying a cross-national, critical perspective with an emphasis on the interplay between science curricula and sustainability issues. Specifically, the selected works examine different curricular aspects, including the contribution of influential educational frameworks and comparative analyses of textbooks and guidelines across various countries. Furthermore, they explore teacher preparedness and the role of co-designed lessons involving researchers, scientists, and teachers to translate educational aspirations into school practice.

Among the frameworks discussed in this chapter are DeSeCo 2003 (OECD, 2003), the Learning Compass 2030 (OECD, 2019), GreenComp (Bianchi et al., 2022), the new Guide for Climate Literacy (USGCRP, 2024) and PISA 2025 (OECD, 2023) — including the concept of Agency in the Anthropocene (White et al., 2023, 2024). Among the studies examining curricular guidelines and textbooks, Watson and Li present a content analysis of curricular documents in Canada and Taiwan, based on the PISA 2025 framework. Following a similar approach, Dawud et al. focus on the presence of dynamic equilibrium as a key concept in Israeli and Manitoba textbooks. Climate Change Education (CCE) is the focus of the textbook content analysis conducted by Lampoudis and Mogias in Greece, as well as that by Tytler et al. in Finland, Australia and Taiwan.

The work by Tytler et al. presents two further studies aimed at identifying opportunities and systemic constraints for CCE. The first of these additional explorations was a cross-national survey of teachers' knowledge, practice, and confidence in teaching CCE. The second exploration involved a process of co-designing research-based sequences through iterative cycles of evaluation and improvement. This evaluation was based on observations, interviews and students' pre- and post-tests. The cross-national insights presented contribute to sharpening our

understanding of how science education can support CCE as well as the contextual factors that frame the possibilities for innovation.

The work by Scarongella analysed several international competence frameworks providing an important reference point to curriculum shaping, with a view to the introduction of sustainability education. The analysis reveals an evolution from literacy-based, economics-driven skills to fostering transformative agency for sustainability. The emphasis on sustainability, especially in GreenComp, PISA 2025 (Bianchi et al., 2022) and "Learning Compass 2030" (OECD, 2019) marks a shift from training knowledge-based competence to cultivating change agents who can think systemically, collaborate, and foster hope to collaborate on climate challenges actively. It is worthy to mention the introduction of the concept agency, defined as “the belief that students have the will and the ability to positively influence their own lives and the world around them, as well as the capacity to set a goal, reflect and act responsibly to effect change" (OECD, 2019). Three key developments stand out from the analysis conducted by Scarongella: the evolution of sustainability from a marginal concern to a central guiding principle, transforming it from "a theme among many" into a paradigm through which education itself must be rethought; the incorporation of agency-related concepts and the redefinition of teachers as catalysts for transformation, highlighting the pending need to translate aspirations to concrete curriculum strategies.

Watson and Li highlight the importance of promoting scientific literacy as a central goal of science education to thrive in an era of uncertainty. Specifically, they present the results of a comparison between the Taiwan and Manitoba science curricula (grades 7-9), which share a similar structure, using the PISA 2025 Science Framework that emphasises scientific literacy through the development of scientific competencies. According to the content analysis, while both curricula align with PISA 2025 in content coverage, they fall short in fostering epistemic and procedural knowledge or general scientific competencies, and a sense of science identity, suggesting key areas for improvement. The authors argue that PISA should not be treated as the sole measure of education quality, but it can serve as a useful tool to identify gaps and inform directions for curriculum development.

In a different context, Dawud et al. focus on the importance of Dynamic Equilibrium (DE), a structuring concept in learning natural sciences that fosters students’ systems thinking. The study presents a qualitative mixed-methods content analysis of the content and representations related to DE in the main high school textbooks and national standards of Israel and the US across biology, chemistry, and physics. According to the findings, DE-related phenomena are present in roughly 14% of science curricula, though not always explicitly. While students struggle to connect microscopic processes with macroscopic phenomena, computational models appear valuable for improving systemic understanding. The study recommends developing unified, cross-disciplinary representations of DE and suggests that future research should explore its integration across more scientific fields.

Lastly, the work by Lampoudis and Mogias highlights the value of the recently updated Climate Literacy Guide (USGCRP, 2024) and advocates for it as a solid foundation for raising students’ climate literacy in formal education. Taking this guide as a referent framework, these authors investigate the presence of climate change issues in Greek Special Education science textbooks. The content analysis shows rather limited and fragmented information concerning the eight essential principles and the seventy-six fundamental concepts of the Guide, identifying key areas for improvement.

We hope that this chapter contributes to sharpening our understanding of the contextual factors that support or hinder responsive and innovative education, while stimulating debate about how

best to prepare students to address current societal and environmental challenges through science education.

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ESERA 2025 Copenhagen

he Evolution Of Competence And Agency In Science Education: A Conceptual Analysis

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The development of competence in science education reflects a significant shift from literacy-focused, economically driven models to comprehensive frameworks that incorporate transformative agency and sustainability. This study traces the conceptual journey from Aristotle's fundamental distinction among episteme, techne, and phronesis—which already highlighted the ethical aspect—through modern frameworks such as OECD DeSeCo 2003, Learning Compass 2030, GreenComp 2022, and PISA 2025. The analysis shows how competence has progressed from simply acquiring knowledge to the ability to act within complex socio-ecological systems, illustrating the enduring presence of Aristotelian ethical components over centuries. Three key developments stand out: the evolution of sustainability from a marginal concern to a central guiding principle; the incorporation of agency-related concepts (systems thinking); and the redefinition of teachers as catalysts for transformation. In particular, values and ethical responsibility in current frameworks have experienced a revival—from DeSeCo's economic focus to PISA 2025's —that reflects a return to the holistic roots of competence. Yet, a persistent tension remains between these comprehensive visions and their practical realisation. This analysis underscores both the persistent influence of ethical dimensions from Aristotle to today and the ongoing challenge of translating transformative aspirations into practical curriculum strategies for the Anthropocene.

Keywords: sustainability agency, science education, competence

Introduction

Over the past three decades, competencies have become a key topic in European and international debates. In Europe, this policy began with the European Council's December 2006 recommendation on key lifelong learning competences, which influenced Italy and other EU countries. Student competencies are divided into four areas: languages, mathematics, science-technology, and social history, later adding citizenship skills. Anyway, despite growing interest, schools struggle to define essential competencies and what it means to develop them (European Council, 2006).

Nevertheless, competencies must be defined to provide students not only with knowledge content but also with holistic, complex skills and attitudes that enable them to navigate an increasingly challenging and uncertain society. In this context, knowledge alone is insufficient; systemic thinking, critical analysis, and ethical judgment are also essential. This is particularly evident in a society and era where the climate and sustainability emergency has gained significant importance, especially in recent years, leading to personal and general uncertainty.

At the international level, attention to the competence topic began in 2003 with the emergence of the first frameworks that began discussing competencies, such as the OECD DeSeCo. However, the historical origin of competence dates back considerably further. Indeed, as Pellerey analysed in his book “Competenze”, the philosophical foundations of competence can be traced back to Aristotle (4th century BC), who already provided a complex and holistic definition of competence. He distinguished between episteme (theoretical knowledge), phronesis (ethical wisdom), and techne (technical ability). Aristotle, therefore, was the first to highlight the importance of conceiving knowledge not only in terms of practical action but also as

encompassing a much more holistic and complex dimension, emphasising the ethical and moral dimension (Pellerey, 2010).

The legacy of this can be noticed, considering that recently the evolution of the concept of competence has shifted from an economic drift—oriented satisfying society's financial needs and requirements, as exemplified by DeSeCo, to more complex aspects of the individual who tends to value ethical and moral agency aspects in the challenges and choices of society.

The explicit introduction of sustainability competence into the European Key Competences Framework occurred with the 2018 Recommendation (European Council, 2018), in response to the global challenges articulated in the United Nations' 2030 Agenda (United Nations, 2015). This integration rendered environmental sustainability a transversal component spanning multiple key competences, with particular emphasis on scientific, citizenship, and entrepreneurial competences (European Council, 2018). It's clear that a significant transition has occurred from the literacy model of the 2000s—articulated around linguistic, mathematical, and scientific competencies—to a comprehensive sustainability-oriented paradigm. Also, the OECD has been forward-thinking in this regard, placing sustainability as a **central priority**, even if its central role has only recently been recognised in PISA-25, with some aspects already addressed in the OECD Learning Compass 2030. Besides, the OECD has been forward-thinking in its approach with respect to the evolution of the literacy paradigm, shifting from a focus on practical skills to fostering transformative capacity. In 2019, following the European Green Deal (European Commission, 2019), which established sustainability as a central EU priority, the integration of sustainability into education was significantly accelerated, transforming it from "a theme among many" into a paradigm through which education itself must be rethought. GreenComp comes up within this revolutionary context. The year 2020 marked a pivotal shift, during which the Joint Research Centre conceived GreenComp as a framework explicitly dedicated to sustainability competencies (Bianchi et al., 2022). This last framework encompasses systemic complexity, ethical dimensions, critical thinking, and uncertainty management, thereby promoting active and transformative citizenship.

In this work, we want to provide a comparative analysis of the conceptual, structural, and purposive evolution of international institutional frameworks, particularly about the emergence of transformative and sustainable dimensions, to review competence in science education. In relation to this, the research question is the following:

How has the concept of competence evolved in science education to address sustainability challenges and transformative agency?

Methodology

To address our research questions, we implement a comprehensive scoping review methodology to map and analyse the historical trajectory and conceptual development of competence and agency in science education. This methodological approach proves particularly valuable for investigating complex, cross-disciplinary subjects that necessitate comprehensive concept mapping, gap analysis, and theoretical integration across multiple perspectives (Arksey & O'Malley, 2005). Our research process follows five systematic stages:

Stage 1 - Research Question Development: Our investigation examines how competence, specifically sustainability competence, has evolved in science education, using international and European conceptual frameworks.

Stage 2 - Literature Identification: We conducted an extensive review of seminal works ranging from OECD-DeSeCo (2003), to more recent educational frameworks, including the OECD Learning Compass 2030 (2019), GreenComp (2022), and PISA Science Framework 2025.

These frameworks were selected because they represent both policy-driven and academic contributions that have significantly shaped the development of the concept of competence. They provide insight into the evolution of competence by offering a reading that is grounded in the relationship between education and society. Furthermore, these frameworks enable us to trace the emergence and institutionalisation of sustainability competences as a concept—from its first academic articulation to its current status as a central dimension of international and European educational policy.

Stage 3 - Selection Process: We established specific inclusion parameters centred on theoretical frameworks of competence and agency in education, while deliberately excluding research focused solely on specific scientific content knowledge.

Stage 4 - Data Analysis: The analysis focuses on key aspects, including tracking the development of competence as a concept, observing the emergence of transformative competences, and examining the gradual integration of values and ethics. We systematically coded whether sustainability was explicitly included or omitted in each framework, enabling the identification of patterns in sustainability incorporation. Finally, we analysed the persistence and evolution of the classical Aristotelian structure and potential implications for curriculum applicability.

Stage 5 - Synthesis and Documentation: Our findings are presented comprehensively, highlighting both the continuity and evolution of competence and agency concepts, with a specific focus on their implications for science education.

The following section presents our analysis, which reveals a gradual evolution from economically oriented competence definitions toward frameworks that emphasise transformative agency, values, and sustainability. Here, we present the key frameworks chronologically, highlighting the conceptual shifts and emergent themes."

Results And Discussions

The Evolution Of The Concept Of Competence In Major Frameworks In Science Education

The following section highlights three phases in the development of competence: the economic-focused phase (1997-2003), the transformative and agency-oriented phase (2018-2019), and the sustainability-centred phase (2020-2025). Throughout this progression, the traditional tripartite model—reflecting Aristotle's distinction among episteme (knowledge), techne (skills), and phronesis (ethical wisdom)—remains but evolves, with values and ethical considerations gaining increasing importance.

At the educational level, two key frameworks at the European and international levels that provide essential guidance for shaping educational paths are the OECD framework for different periods and GreenComp. Comparing these frameworks will specifically highlight how and why the concept of competence shifts from a simple understanding, such as knowledge, to a more complex and articulated notion. This will also be analysed in relation to societal change, as well as the historical origin and initial purpose of the framework. The emergence of environmental competencies over time will also be examined. The first frameworks to be analysed are the OECD frameworks across different periods, starting with their origin. The OECD (Organisation for Economic Co-operation and Development) is an international organisation founded in 1961 to promote policies that improve the economic and social well-being of people worldwide by

reducing disparities, poverty, and social inequalities. His birth occurred after the Marshall Plan, established by the United States after World War II to address Europe's economic crisis. Its predecessor was the **Organisation for European Economic Co-operation (OEEC)**, which coordinated the distribution of financial aid and helped European countries rebuild their economies by promoting economic cooperation, and was active from 1948 to 1961. It primarily focused on managing the Marshall Plan and post-war economic reconstruction, with a limited scope confined to Europe. The OEEC had not yet developed a competency framework. During this period, due to social needs, the emphasis shifted to technical and professional education, with a focus on practical knowledge and skills. This approach was adopted to better address the socio-economic problems faced at that historical time. Then, in 1961, the OECD was born to serve as a source of information, providing economic data, policy analyses, and recommendations to its 38 member countries, both European and non-European (OECD, n.d.).

Over time, the OECD has expanded its sphere of action from a purely economic area to one that first concerns education and then also the environmental aspects. For the first time, the concept of competence was introduced in 1997 when the **DeSeCo-Defining and Selecting Key Competencies** project was launched by the OECD and concluded with the final report in 2003 with **"Key Competencies for a Successful Life and a Well-Functioning Society"**, to provide a conceptual framework for identifying key competencies necessary for modern life (OECD, 2003). The definition of competence is the following, given on page 4 in OECD DeSeCo Project: *"A competency is more than just knowledge and skills. It involves the* **ability to meet complex demands** *by drawing on and mobilising psychosocial resources (including skills and attitudes) in a particular context"*(OECD, 2003, p. 4). It is clear that in this definition, the economic dimension remains fundamental, and while the social benefits are present, they are not essential. The document that follows DeSeCo and most comprehensively encompasses the ongoing changes in competencies is the new **OECD Learning Compass 2030** framework, published in **2019.** The **OECD Learning Compass 2019** is a guidance tool designed for all actors in the educational system, from policymakers to students and their families. It arises from the need to redefine the competencies necessary for 2030 and guide educational systems in addressing future challenges. It is a framework, not designed like DeSeCo, that represents an expansion of the previous one towards a concept of competencies with a connotation related to **agency, co-agency, and transformative competencies.** This framework first introduced the word agency: "*Student agency is defined as the belief that students have the will and the ability to positively influence their own lives and the world around them as well as the capacity to set a goal, reflect and act responsibly to effect change*" (OECD, 2019, p. 17). White et al. (2023) later further developed this idea for sustainability by defining individual and collective agency using measurable constructs such as hope, self-efficacy, and outcome expectancy. The framework expands by, for the first time, including not only knowledge and skills for professional use but also attitudes and values. This explicit inclusion of values marks a return to the holistic conception of competence, recalling Aristotle's phronesis (ethical wisdom). Competencies are seen as tools for navigating the uncertainties and complexities of the modern world, defining the skills students must acquire to face future challenges. The peculiarity of this framework is to identify three transformative competencies (creating new values, reconciling tensions and dilemmas, taking responsibility) and a series of values and attitudes that students must develop to be responsible citizens (respect for self, others, country, diversity, empathy, integrity and resilience). This is the definition of competence given in the document: "*A competency is a holistic concept that includes knowledge, skills, attitudes and values. The OECD Future of Education and Skills 2030 project defines a competency as more than just 'skills". Skills are a prerequisite for exercising a competency. To be ready and competent for 2030, students need to be able to use their knowledge, skills, attitudes*

and values to act in coherent and responsible ways that change the future for the better" (OECD, 2019, p. 25).

Also, the OECD logo effectively conveys the framework's structure and founding message (see OECD, 2019, p. 24). It can be described as follows: a compass can be observed with student agency at its centre, enabling them to become active protagonists of their own learning and capable of making conscious decisions. The competencies provided by the Learning Compass (knowledge, skills, attitudes, and values) are fundamental for navigating a complex, continually changing world. They must work together to build a shared sense of wellness. At the base of the compass are the "Core foundations" (basic foundations), which are the competencies that constitute a premise for the development of any other competency. These foundations encompass cognitive competencies (including literacy, numerical competency, digital literacy, and data literacy), health (including physical and mental well-being and individual well-being), and social-emotional skills (moral and ethical). These foundations are also functional to the development of three transformative competencies: creating new values, reconciling tensions and dilemmas, and taking responsibility. In particular, creating new values means "*Creating new value refers to a person's ability to innovate and act entrepreneurially, in a general sense, by taking informed and responsible actions*"(OECD, 2019, p. 62). The concept of co-agency is also evident in the figure, which illustrates collaboration among students, teachers, families, and the broader community. While student agency is defined as the belief that students have the will and ability to positively influence their own lives and the world around them, as well as the capacity to set goals, reflect, and act responsibly to produce change. Because it is only through the joint work of multiple actors that one can achieve everyday wellness. Moreover, knowledge is intended to encompass theoretical concepts and ideas that extend beyond practical understanding, grounded in experience performing specific tasks. Besides, it recognises four different types of knowledge: disciplinary, interdisciplinary, epistemic, and procedural. And finally, skills are understood as the ability to perform processes and use one's knowledge responsibly to achieve a goal, which distinguishes between four types of skills: cognitive and metacognitive, social and emotional, practical, and physical. Lastly, attitudes and values refer to the principles and beliefs that influence a person's choices, judgments, behaviours, and actions on the path towards individual, social, and environmental well-being. Moreover, in the 2018 position paper (The future of education and skills 2030), the urgency of creating an educational system that addresses not only economic and social challenges but also environmental ones (including the depletion of natural and climate resources) is highlighted. In both documents, the ecological theme is consistently presented as one of the challenges to be addressed, but not the only one (OECD, 2018).

The Rise Of Sustainability Competences

What follows reveals a critical turning point around 2020: in this year, sustainability shifted from being one challenge among many to becoming a central dimension of educational competence. The following section examines this transformation through GreenComp and PISA 2025, which shows how sustainability competences have been systematically integrated into contemporary educational frameworks.

Analysis shows a shift in the role of sustainability in frameworks. Before 2020, sustainability competence was minimal or embryonic, but from 2020 onwards, it gained importance. According to GreenComp (2022), it became central to educational competencies, reflecting the urgency of the climate crisis and a shift from training competitive workers to shaping change agents within planetary boundaries (Bianchi et al., 2022).

GreenComp belongs to the five frameworks developed by the European Union (LifeComp, EntreComp, DigComp, GreenComp, and Competences for a Democratic Culture), which specify

additional, more detailed competences that allow for a more precise definition of the objectives within the eight key competences (Bianchi et al., 2022).

It differs from the first in that it was specifically created to address environmental and climate-related issues, and it is European rather than international. The GreenComp (European Sustainability Competence Framework) is aimed at educators, trainers, policymakers, and students of all ages. It was created by the European Commission in 2022 through the Joint Research Centre (JRC) and aims to provide a reference framework for teaching and learning sustainability-related competencies. This framework guides the integration of sustainability-related competencies into educational and training systems. The main objective, therefore, is to help people develop the knowledge, skills, and attitudes necessary to live, work, and act sustainably.

In it, sustainability is defined as: "sustainability means prioritising the needs of all forms of life and the planet, ensuring that human activity does not exceed the planet's limits". GreenComp, therefore, tends to foster an image of sustainability that balances nature and humans and develops in humans an awareness of their own limits.

In this framework, competencies are consistently linked to sustainability: "A sustainability competence enables learners to embody sustainability values and accept complex systems, to act or request actions that restore and maintain ecosystem health and increase justice, by envisioning sustainable futures". The teaching/learning of sustainability, therefore, aims to develop a sustainable mindset throughout the entire lifespan, from childhood to adulthood, promoting awareness that human beings are an integral part of nature and depend on it. Through greenComp, students gain knowledge, skills, and attitudes that empower them to be agents of change. They contribute both individually and collectively to create a future that respects the Earth's ecological boundaries. In the framework, the following definition of competence is given: *"a dynamic combination of knowledge, skills, and attitudes"*. Specifically, the GreenComp articulates competence into 12 competencies organised into four main areas: sustainability values, systemic thinking, sustainable future, and sustainability action.

These peculiarities ensure that GreenComp focuses not only on knowledge acquisition but also on the ability to act for change, promoting sustainable development at both personal and collective levels. As can be seen, all four areas refer to different approaches: some are more practical and action-oriented, while others are more theoretical, focusing on the development of mental strategies. It is important to note that GreenComp also emphasises the value dimension. Still, unlike the Learning Compass ‘30, it highlights three specific values related to sustainability: valuing sustainability, supporting fairness, and promoting nature.

Furthermore, the authors of the framework use a pollination metaphor to represent how the different areas of the framework are interconnected (see Bianchi et al., 2022, p. 12). In this scheme, the bees symbolise the 'acting for sustainability' area, as each bee plays a fundamental role in the colony's well-being and collaborates to achieve common goals. The flowers represent 'imagining sustainable futures' because they produce new fruits and seeds, fostering continuous renewal. The hive represents 'embodying the values of sustainability' as it protects and supports the bees. Finally, the pollen and nectar, which attract the bees to the flowers, symbolise the 'accepting the complexity of sustainability' area. This image thus highlights an ecosystemic vision where everything is interconnected.

GreenComp's ecosystemic vision exemplifies a growing trend where sustainability is no longer just one aspect but a key, organising element in education. This change is clearly demonstrated

by PISA 2025, marking a significant shift in how the idea of competence in science education has developed.

PISA 2025 exemplifies a crucial new phase in the conceptualisation of competence within science education. The omission of the term "literacy" from this framework indicates a significant transition: it is no longer only concerned with students' capacity in science, but also emphasises their connection to the subject.

A key innovation in PISA 2025 is the concept of "Agency in the Anthropocene," which aligns with the OECD Learning Compass 2030's transformative vision but explicitly emphasises sustainability. The core competencies assessed include understanding how human actions affect Earth systems, making decisions informed by evaluating various evidence sources, applying creative and systemic thinking to sustain and regenerate the environment, and respecting diverse perspectives while maintaining hope in addressing socio-ecological challenges (White et al., 2023).

PISA 2025 attributes particular relevance to sustainability and environmental education, not as a separate theme but as a transversally integrated dimension. A person with scientific preparation must be capable of engaging in reasoned discourse on science, sustainability, and technology to inform action.

The supporting document 'Agency in the Anthropocene' (White et al., 2023) offers theoretical insights into these competencies, explaining the concepts of hope, self-efficacy, and outcome expectancy. It also distinguishes between individual aspects (such as critical evaluation and personal resilience) and collective aspects (such as consensual decision-making and action across various scales) of agency.

The analysed frameworks reveal varying curriculum specificity. Some provide operational guidance through detailed competency descriptors that break down knowledge, skills, and attitudes (GreenComp, Appendix 2), practical scenarios that demonstrate real-world application (GreenComp, Appendix 1), and specific pedagogical approaches, including active learning, place-based education, and systems thinking. Others explicitly clarify their non-curricular nature (OECD Learning Compass 2030), offering generic principles without operational indicators. Regarding the teacher's role, all frameworks reject transmissive models, positioning teachers as "transformative facilitators" who co-construct learning with students, model sustainability values, and facilitate democratic processes. The concept of co-agency is strongly evident, yet frameworks offer minimal guidance on preparing teachers for these demanding roles or on transitioning from current practices.

Conclusions

The evolution of competence frameworks from DeSeCo (2003) to PISA 2025 reveals a shift from literacy-based, economics-driven skills to fostering transformative agency for sustainability. Tracing the evolution from Aristotle's complex structure (episteme, techne, phronesis) to modern models, it shows both continuity and change in the integration of knowledge, skills, and ethics. The emphasis on sustainability, especially in GreenComp, PISA 2025, and "Learning Compass 2030," marks a shift from training knowledge-based competence to cultivating change agents who can think systemically, collaborate, and foster hope to collaborate on climate challenges actively. However, a tension exists between holistic visions and practical application: while frameworks promote interconnected approaches, they also need some metrics that may fragment curricula. All agree on shifting from transmissive to transformative and co-constructive teaching roles, which lack clear guidance and have no standard methods for transversal skills. Sustainability education faces the challenge of turning transformative visions into a practical

curriculum. Future efforts should create concrete pathways for holistic integration and provide teachers with support and tools to empower students amid the complexities of the Anthropocene.

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Ready for PISA 2025? A Comparative Analysis of Taiwan and Manitoba Science Curricula

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The PISA 2025 framework shifts focus from scientific literacy to scientific competencies, emphasizing the ability to apply knowledge effectively as a key aspect of scientific competence. Given this radical shift, we, as teacher educators, wonder whether our current curricula are preparing students to succeed in the updated PISA framework. Although using a specific test as an evaluation mechanism for the overall curriculum is problematic, the PISA 2025 can provide a systematic method to understand whether students possess the critical competencies needed to face the rapidly changing modern society. This study employs a document analysis method, using the PISA 2025 Science Framework to analyse the science curriculum guidelines for grades 7 to 9 in Taiwan (TWN) and Manitoba (MB), Canada. Results reveal the curricula in both TWN and MB are lacking in procedural knowledge and epistemic knowledge, which is a major critique of modern curriculum guidelines. In terms of context, both TWN and MB have a significant gap compared to the PISA 2025 goals. This might make it more challenging for students to deal with scientific problems in various situations. Finally, regarding science identity, the analysis results reflect the environmental differences between TWN and MB. To summarize, both the TWN and MB science curriculum documents have rich content knowledge, but they fall short of the PISA 2025 goals in other aspects. This study provides a potential direction for curriculum developers and further expands the possibilities for teaching scientific literacy and the nature of science. Although the PISA 2025 framework is not perfect, it serves as a meaningful goal for continuous improvement.

Keywords: PISA 2025, Science Curriculum, Comparative Analysis

Introduction

Since 2000, Programme for International Student Assessment (PISA), one of the most influential, international, student learning assessments (McGaw, 2008), has used a globally recognized framework to assess the performance of national education systems. In 2023, a new assessment framework in PISA 2025 Science Framework (PISA 2025) was unveiled and it prioritized scientific competencies, marking a departure from the previous structure, which focused on scientific literacy.

Scientific literacy is a goal of education, yet scholars cannot agree on its definition (DeBoer, 2000; Osborne & Allchin, 2024). DeBoer (2011) called for science education to determine the knowledge and competencies needed for global citizenship. Scientific literacy points to a diverse set of aims for society and citizens (Osborne, 2023), whereas scientific competencies focus on those skills required for a person to engage in reasoned discourse about science (OECD, 2023). Shifting from literacy to competencies implies the goals of science education, under PISA 2025, are defined in terms of what an individual can do with their knowledge instead of by what they know. Competencies opened space to consider more types of knowledge, such as epistemic knowledge (Zetterqvist & Bach, 2023), than previously included in PISA efforts.

This new framework brings the preparedness of science education curricula to meet PISA expectations into question. Are students in our contexts ready for PISA 2025? To answer this, we compare the contexts of Taiwan and Canada. Despite their geographical distance, these two nations share striking historical and cultural parallels; both are multicultural societies with deep

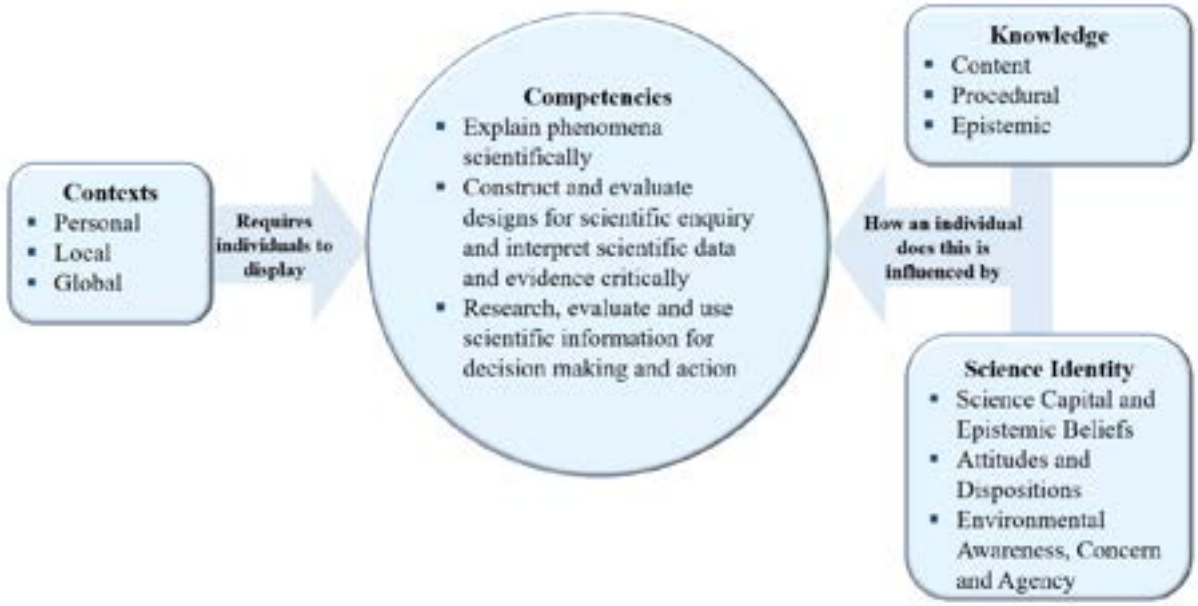
Indigenous traditions, and both have evolved into their current state following histories of European colonization. However, their geographical distinctions, Canada as a vast continental landmass and Taiwan as an island nation, expose them to different Socio-Scientific Issues. These environmental differences inevitably influence the design philosophies of their respective science curricula.

Regarding the selection of specific regions, education in Canada falls under provincial jurisdiction rather than a federal mandate. Consequently, this study selects the province of Manitoba (MB) as a comparative basis, a choice further motivated by the researchers' geographical location and familiarity with the local context. While Taiwan adopted a revised national curriculum in 2019, at the time of this research Manitoba's framework was unchanged since the early 2000s. Since both contexts use curriculum documents developed before PISA 2025, we questioned whether our curriculum contexts prepared students for PISA. That is, are PISA 2025's knowledge, context, and science identity components appropriately represented in Taiwan's curriculum guidelines (2019) and Manitoba's curriculum framework (2000)?

Study Design

The curriculum documents of Taiwan and Manitoba share a similar structure, both using lists of verb-centric outcomes. The Taiwan document has 255 specific learning outcomes, and the Manitoba document has 375. Both curriculum documents include multiple, content-focused units/topics and separate sections with outcomes intended to be woven throughout the course(s). In Manitoba, these separate sections focused on science inquiry, the design process, and scientific literacy. In Taiwan, these separate sections focus on scientific attitudes, inquiry, and cognition and on those aspects of science across content-topics.

Figure 1. PISA 2025 Framework (OECD, 2023, p.11)



Document analysis (Bowen, 2009), specifically content analysis, was used to evaluate the curriculum documents. PISA 2025 served as our a priori framework. Based on the "outcomes of science education" proposed in PISA 2025 (Figure 1), this study analysed each item in Taiwan and Manitoba grades 7-9 science curriculum documents; the PISA exam is taken in grade 9 in both countries, so we focused on grades 7-9. Each outcome item within the curriculum documents

was coded using the sub-frameworks describing the *types of knowledge*, *context*, and *science identity*; general descriptions of each of these sub-frameworks are provided in Figure 1. full descriptions available in PISA 2025. Items could represent multiple aspects under each of these sub-frameworks. For example, the outcome of "Investigate Canadian and international contributions to research and technological development in the field of genetics and reproduction (MB S1-1-16)" was coded as representing content-knowledge (life sciences), both local and global contexts, and science capital and epistemic beliefs.

To ensure inter-coder reliability, two researchers independently coded each document. Through an iterative process, results were compared and any discrepancies resolved through discussion.

Results

Codes were amalgamated and, where possible, compared to PISA 2025's expectations. Charts from each of these sections will serve as focal points for prompting discussion.

Knowledge

As shown in Figure 1, PISA 2025 labels knowledge as content, procedural, or epistemic knowledge. The knowledge content was further described by the systems of physical sciences (i.e., physics and chemistry), life sciences (i.e., biology), and earth and space sciences (i.e.., geology and astronomy). During our analysis, we noted that both documents were highly focused on content knowledge, so we chose to consider both the procedural and epistemic knowledge in terms of the physical, living, and earth and space sciences.

Table 1. Distribution of Knowledge Outcomes.

		Content	Procedural	Epistemic
Physical	PISA	15-20%	10-13%	8-11%
	MB	27.7%	4.5%	2.9%
	TWN	41.2%	0.0%	0.4%
Living	PISA	15-20%	10-13%	8-11%
	MB	16.0%	1.1%	1.3%
	TWN	27.8%	0.4%	2.0%
Earth & Space	PISA	10-15%	7-10%	7-10%
	MB	10.9%	1.1%	2.9%
	TWN	21.6%	0.0%	1.6%
Content General	MB	7.7%	1.9%	1.1%
	TWN	3.1%	1.6%	2.0%
Not Content	MB		15.5%	9.3%
	TWN		7.1%	3.9%

Further, some outcomes in both documents did not address knowledge specific to physical, living, or earth and space science but did address some type of content knowledge in science as defined by PISA 2025 (pp. 24-26); hence, we added a knowledge type, "Content General". For instance, the outcome "The process and applications of various materials in life (TWN Mc-IV-3)" illustrates procedural understanding that pertains to general science rather than any specialized subject.

On the other hands, some outcomes did not connect to content knowledge but connected to procedural or epistemic knowledge; we identify these outcomes as "Not Content". For example, the outcome "Students can properly connect acquired knowledge to observed natural phenomena and experimental data, in order to make inferences, see correlations, and justify their arguments (TWN tr-IV-1)" demonstrates how to link phenomena and data to scientific claims. This reflects a deep understanding of methodology and epistemology, independent of specific content knowledge.

Table 1 (above) presents the distribution of outcomes for knowledge in both curriculum documents, Manitoba (MB) and Taiwan (TWN). PISA 2025 defines target distributions for the assessment of knowledge (OECD, 2023, p. 43), see left-most column under each physical, living, and earth and space knowledge in Table 1.

Table 2. Distribution of Context Outcomes.

		Personal	Local/National	Epistemic
Physical	MB	1.3%	0.5%	0.5%
	TWN	1.9%	0.0%	0.3%
Living	MB	1.6%	1.9%	2.7%
	TWN	1.3%	1.9%	2.9%
Earth & Space	MB	0.0%	1.6%	1.3%
	TWN	0.3%	2.4%	1.6%
Content General	MB	0.3%	0.3%	0.5%
	TWN	0.5%	0.0%	0.0%
Not Content	MB	4.8%	2.9%	2.4%
	TWN	1.1%	0.5%	0.8%
Total	MB	8.0%	7.2%	7.5%
	TWN	5.1%	4.8%	5.6%

Science Identity

PISA 2025 does not explicitly state the expected distribution of science identity. Schiepe-Tiska et al.'s (2016) identity assessment framework suggests that the four dimensions of science identity

are equally important. Similar to context results, we present PISA 2025 aspects of science identity and the aspects of content knowledge as percentages of total outcomes (Table 3).

Table 3. Distribution of Science Identity Outcomes.

		Science Capital	Epistemic Beliefs	Attitudes & Dispositions	Environmental Awareness
Physical	MB	0.8%	0.3%	0.3%	0.3%
	TWN	1.2%	1.2%	0.0%	1.2%
Living	MB	0.5%	0.3%	0.0%	1.9%
	TWN	0.8%	3.1%	0.8%	9.0%
Earth & Space	MB	0.3%	0.0%	0.0%	1.1%
	TWN	0.4%	0.4%	0.0%	5.5%
Content General	MB	0.0%	0.0%	0.0%	0.8%
	TWN	1.2%	0.8%	1.2%	0.0%
Not Content	MB	2.9%	3.7%	5.6%	2.7%
	TWN	3.1%	3.1%	2.0%	0.4%
Total	MB	4.5%	4.3%	5.9%	6.7%
	TWN	6.7%	8.6%	3.9%	16.1%

- Standard Deviation for total: MB(1.1%), TWN(5.2%)

Discussion

Both Manitoban and Taiwan documents focus on preparing students for content knowledge rather than procedural or epistemic knowledge. The Taiwan document had a higher percentage than PISA 2025 expectations in every knowledge content area; the physical science content representation (41.2%) doubled the expectation of PISA 2025 (15-20%). Manitoba also focused on physical science knowledge. Both documents' inclusion of non-content-knowledge outcomes may have skewed percentages.

The distribution of outcomes representing each content area in both documents exceeded PISA 2025 expectations. However, the heavy weighting of the content knowledge in both the TWN and MB curriculum documents suggests a heavy focus on science as content in education. This was particularly evident in both contexts heavily emphasizing physical science, with TWN having over 40% and MB having almost 30% of their outcomes reflecting physical science content. This emphasis on content knowledge is inadequate to develop the necessary informed epistemic trust needed by students today to sift through the misinformation bombarding their lives today (Osborne & Allchin, 2024). It is with this in mind, that we recognize that while both TWN and MB students may be exposed to the knowledge content necessary to succeed with PISA 2025, we contend that neither curriculum document may be adequately preparing students for the entirety of PISA 2025.

Both documents had low representation of procedural and epistemic knowledge. Manitoba's document showed a higher representation of procedural knowledge than Taiwan's document. Procedural outcomes in both countries were often not connected to science content. Taiwan's document focused more on epistemic knowledge in relation to living sciences and general content knowledge than Manitoba, with Manitoba having higher representation in all other areas. Both documents were below PISA 2025 expectations. We conclude students from both countries should be prepared to answer content-knowledge questions but may be underprepared in procedural or epistemic knowledge.

Neither country had ratios reflecting the context expectations of PISA 2025. Both countries represented personal, local/national, and global contexts relatively evenly whereas PISA 2025 includes a much higher representation of local/national settings. Manitoba had more outcomes connected to each of the three contexts than Taiwan. Taiwan's document showed slight preference towards global contexts and Manitoba's document toward personal context, possibly due to the values toward community held in each context. Consequently, Manitoban students may be slightly more comfortable recognizing science in context than Taiwanese students.

Finally, PISA does not have expected distribution of science identity aspects, but Schiepe-Tiska et al. (2016) suggest equal distribution among each of the aspects; the standard deviation of science identity aspects for Manitoba was 1.1% and Taiwan was 5.2%. This suggests a relatively equal distribution of aspects in the Manitoban document but not in Taiwan's document. Taiwan's document focused on science capital, epistemic beliefs, and environmental awareness more than Manitoba. Taiwan's document emphasizes environmental awareness strongly in relation to both living (9.02% of outcomes) and earth and space (5.49% of outcomes) science; Taiwan is an island nation, and this may be because the impacts of climate change are felt more severely. Manitoba's document focused more on attitudes and dispositions than Taiwan, but very few outcomes connected to any aspect of science identity and content knowledge. We expect Taiwanese students to be more prepared in terms of science identity, particularly environmental awareness.

We conclude that both the Taiwan and Manitoba documents reflect the expected content-knowledge of PISA 2025—in many areas these expectations were exceeded—but are lacking in all other aspects. Of particular concern is the low representation of epistemic knowledge; this is representative of the literature on the inclusion of epistemic knowledge in science education (Zetterqvist & Bach, 2023). Science education prepares citizens for an increasingly uncertain world (Covitt & Anderson, 2022); thus, epistemic knowledge is of more importance than ever, and we hope that future documents will address its underrepresentation.

Conclusion

This study opens discussion about how science curriculum documents may or may not prepare students for PISA 2025. PISA, in many countries, is used to judge the quality of a nation's science education (Zetterqvist & Bach, 2023). We, like many scholars (Au, 2022), recognize the problematic nature of preparing our students for a specific assessment like PISA. However, we argue that while PISA should not be relied upon as the sole indicator of educational quality, it nonetheless offers a valuable directional guide for curriculum adjustment and improvement.

In this light, the PISA 2025 framework provides a way to systematically evaluate the appropriateness of science curriculum documents for grades 7-9 students. Ultimately, this evaluation highlights that science education has evolved beyond a mere focus on content knowledge. To truly equip students with a scientist's mindset, necessary for navigating a rapidly changing future, curricula must go beyond the OECD's competencies and deeply incorporate the nature of science.

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ESERA 2025 Copenhagen

Dynamic Equilibrium In Science: Comparison Between The Israeli And United States Frameworks And Representations In The Standards And Textbooks

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The study examines how Dynamic Equilibrium (DE) is represented in science national standards and textbooks for high-school biology, chemistry, and physics in the US and Israel. DE, a crucial concept in understanding dynamic systems, is inconsistently represented across educational materials and students encounter difficulties learning about DE. Analysing 17 textbooks and national standards, the research combines quantitative and qualitative content analysis to assess the frequency and nature of presentation of DE-related phenomena. The study identifies 256 DE-related phenomena, comprising 14% of all phenomena that are studied in science. The primary systems approach used is System Dynamics, which focuses on stocks and rates of flow at one description level. The main representational format is verbal, and computational models are scarcely used. Differences across disciplines and between countries were found. These findings emphasize the need for powerful representations of DE to enhance students' understanding of dynamic systems and improve science education.

Keywords: Dynamic equilibrium; Science education; Systems thinking; Textbook analysis; Scientific representations; Cross-national comparison.

Introduction, Theoretical Perspectives, And Research Goal

This paper examines the concept of Dynamic Equilibrium (DE) in the US and Israeli high school science standards and textbooks, focusing on its role as a structuring concept across the natural sciences. DE is fundamental for understanding patterns in dynamic systems, describing systems that maintain stability through continuous balancing influences (Biology Dictionary, n.d.), such as homeostasis in biology, ecological systems, and chemical equilibrium. Despite its significance, DE remains a challenging concept for students, with difficulties arising from the contradiction between the system's stable appearance and the dynamic processes that maintain it (Sarıçayır et al., 2006). Students often struggle to understand stability as a dynamic process rather than static constancy, as seen in alternative concepts about chemical equilibrium (Nakhleh, 1992; Özmen, 2008) and homeostasis (Zion & Klein, 2015).

DE is analysed through systems frameworks like System Dynamics (SD; Forrester, 1961), Structure-Behavior-Function (SBF; Hmelo-Silver & Green Pfeffer, 2004), and Agent-Based Modeling (ABM; Wilensky & Rand, 2015). These frameworks focus on understanding system behavior and emergent patterns, helping students grasp the dynamic and parallel nature of equilibrium in complex systems. DE plays a key role in science education, particularly in the NGSS standards, which include Stability and Change as a crosscutting concept related to DE (NGSS, 2013). Proper instruction on DE fosters systems thinking and enhances students' understanding of complex processes across multiple levels of representation. The high school curricula in the US and Israel differ in structure. In the US, students are exposed to a wide range of subjects, with opportunities for specialization through programs like AP courses. In Israel, students specialize in one or two subjects, limiting exposure to other fields. Assessments also vary: in the US, GPA and standardized tests like the SAT or ACT are used, while in Israel, the Matriculation (Bagrut) exams focus on the chosen specialization subjects.

This study is part of a larger international project, which aims to develop better representations of DE to address the identified learning challenges. By comparing national standards and textbooks from both countries, we seek to understand how DE is structured, conceptualized, and conveyed within different educational contexts. The research excludes supplementary or external teaching materials. This research aims to compare how DE is represented in the science curricula and textbooks of the US and Israel and identify the DE-related phenomena and their representational formats. Additionally, it examines how different system frameworks are applied across subjects and countries. Through a cross-national analysis, this study seeks to uncover both expected and unexpected instances of DE in science education, with an emphasis on improving representations to enhance student comprehension of dynamic systems.

Methodology

The study analysed the content and representations related to DE in the main science textbooks and national standards of Israel and the US (Israel Ministry of Education, 2024; US NGSS, 2013; US National Research Council, 2012). A qualitative mixed-methods content analysis (Krippendorff, 2019; Schreier, 2012) categorized DE-related phenomena into seven representational formats: verbal, equation-based, graphical, tabular, photographic, illustrative, diagrams, and computational (e.g., simulations). “Phenomenon” is defined in the analysis as an object-involving occurrence, where an object (or system) undergoes a process, an event, or a state (Kaiser & Krickel, 2017). The analysis focused on the frequency of DE phenomena and the system frameworks used to describe them. This study does not encompass the entire student learning environment, acknowledging that lab work and external resources also play a role in student engagement with DE concepts.

Findings

Content Of The Curricula

An overview of the high school science curricula in the US and Israel was conducted to identify overlap and facilitate comparison. The standards and textbooks’ topics were subdivided into content-based groups, aligning them as categories. The number of phenomena in each discipline in both countries was counted (see Figure 1).

In biology, the curricula in both countries cover similar topics, with some differences in emphasis. Key topics include cellular biology, human and animal biology, and ecological systems. Both countries address cell structure, organelle functions, and processes like respiration and protein synthesis. The US emphasizes substance transport, while Israel teaches fermentation and meiosis in cell division. Both countries teach human and animal biology, including body systems, physiology, and genetics. In ecology, both curricula cover ecosystems and human impact, with the US focusing more on energy flow and succession, while Israel emphasizes human impact and ecological organization. The primary difference is that the US includes evolution and biodiversity, topics absent in Israel.

In chemistry, the curricula in both countries align closely, focusing on similar principles, though differences arise in depth or emphasis. Topics include atomic structure, chemical bonds, energy changes, food chemistry, and chemical equilibrium. Both countries address oxidation-reduction, chemical reactions, and factors affecting equilibrium. The main differences are in the level of detail or emphasis in specific areas.

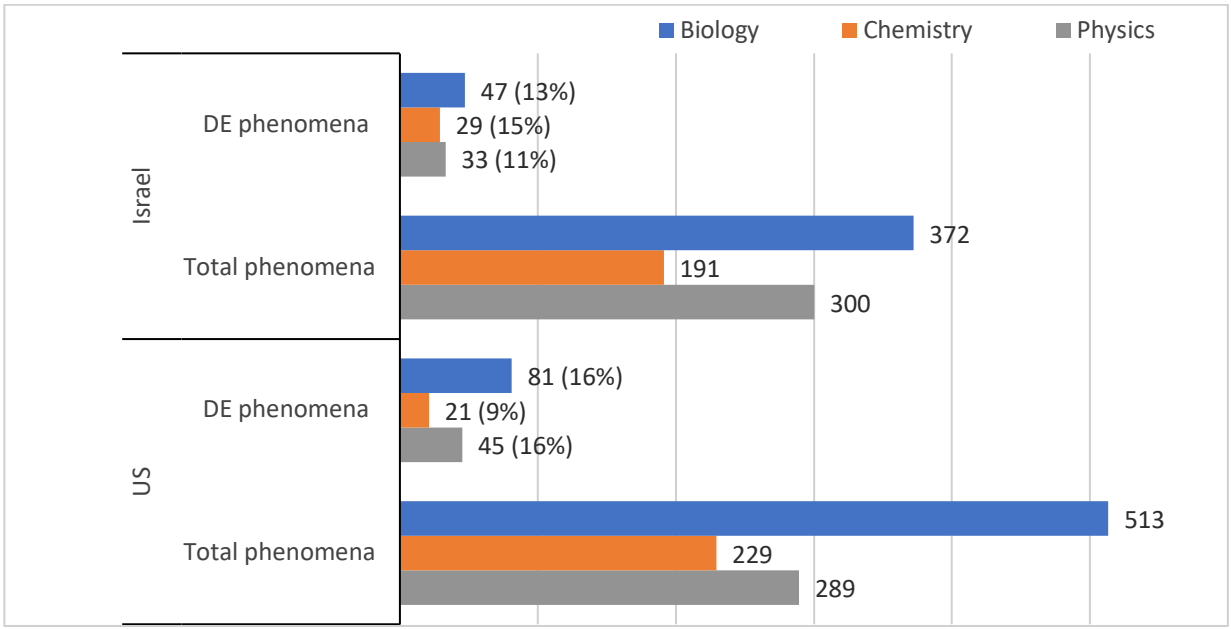
In physics, both curricula cover forces and motion, energy, electricity and magnetism, and radiation and matter, with some differences. For forces and motion, Israel emphasizes Newton's laws and momentum conservation, while the US focuses on force-mass-acceleration relationships

and real-world applications like collisions. Both curricula cover energy, with Israel focusing on mechanical energy and the US highlighting energy transfer and work-energy principles. In electricity and magnetism, both teach electric fields and Ohm's law, with Israel covering electromagnetic induction and the US emphasizing applications like circuits and power generation. In radiation and matter, both curricula address atomic and nuclear physics, with Israel focusing on atomic structure and quantum phenomena, while the US connects these topics to real-world applications like medical technologies. The differences lie in Israel's focus on foundational concepts and the US's emphasis on applications.

Identification And Counting Of DE-Related Phenomena

We identified phenomena embodying the principle of DE in the standards and textbooks, including those not explicitly defined as DE phenomena. The total number of phenomena and DE-related phenomena are shown by discipline (biology, chemistry, physics) for both countries (see Figure 1).

Figure 1. Frequency of All Phenomena and DE-Related Phenomena Across Disciplines (Biology, Chemistry, Physics) in the US and Israel Standards and Textbooks.



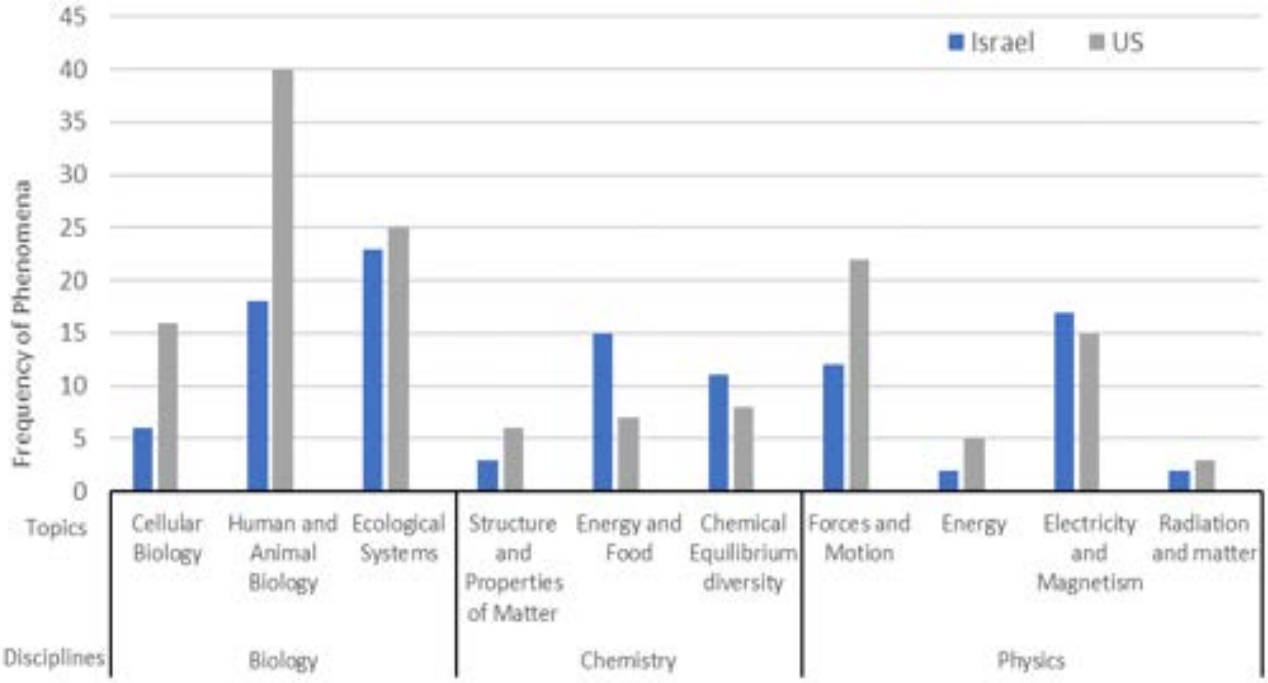
Overall, there are 256 DE-related phenomena across the three disciplines. In the US, 147 DE-related phenomena were identified, making up 14% of all phenomena. In Israel, 109 DE-related phenomena were found, representing 13% of the total. DE-related phenomena are most common in biology, followed by physics, then chemistry. In physics and chemistry, the total number of phenomena is similar between the two countries, but the US has a higher overall number of phenomena. The proportion of DE-related phenomena is greater in the US than in Israel for biology and physics, while in chemistry, Israel has a higher percentage of DE-related phenomena.

Distribution Of DE-Related Phenomena

We identified DE-related phenomena in the standards and textbooks, including those not explicitly defined as DE phenomena. Figure 2 shows the distribution by discipline and topic.The US and Israeli curricula align on half of the ten topics. However, the US includes more DE-related phenomena in forces and motion (physics) and cellular and animal biology (biology), while Israel emphasizes energy and food and chemical equilibrium (chemistry). Of the 256 phenomena examined, 11 describe chemical equilibrium, 27 address homeostasis, and 13 involve ecological systems, all traditionally linked to DE. Notably, 205 phenomena, representing 80% of DE-related

phenomena and 11% of all described phenomena, depict DE processes in topics not previously defined as DE-related.

Figure 2. Distribution of DE-Related Phenomena Across Disciplines (Biology, Chemistry, Physics) and Topics in the US and Israel High School Textbooks.



DE Representations' Format

In future research, we will develop and explore new computational representations for DE. The study examined the prevalence of various representation formats in DE-related phenomena within US and Israeli textbooks, categorized as verbal, mathematical, graphical, tabular, photographic, illustrative, diagrammatic, and computational models (see Table 1).

Table 1. Format of Representations of DE-related Phenomena According to Textbooks in the US and Israel.

			Representation Format (% of N)							
Discipline	**Country**	**Phenomena (N)**	Model	Diagram	Illustration	Photograph	Table	Graph	Equations	Verbal
Biology	UA	81	18	26	48	13	1	5	6	100
	Israel	47	0	42	38	27	22	27	9	100
Chemistry	US	21	0	25	63	17	8	25	79	100
	Israel	29	3	0	11	0	24	29	34	100
Physics	US	45	0	20	76	20	4	31	73	100
	Israel	33	0	8	82	10	8	13	62	100

The study examined the prevalence of various representational formats in DE-related phenomena within US and Israeli textbooks, categorized as verbal, mathematical, graphical, tabular, photographic, illustrative, diagrammatic, and computational models. Overall, the frequency of representation formats follows the order: verbal > illustration > mathematical > diagram > graph

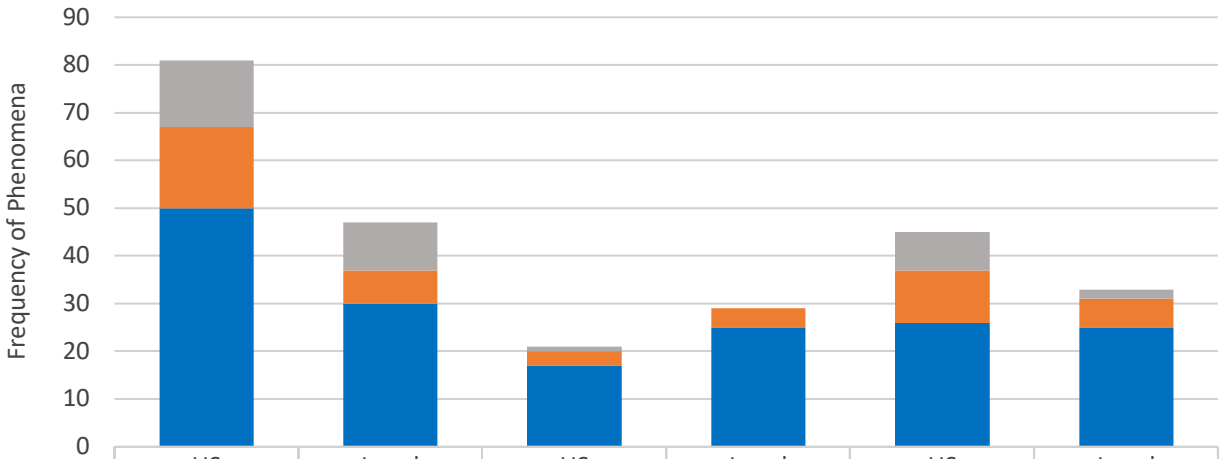
> table > computational model. Israeli biology textbooks feature six representation types in at least 20% of sections, compared to three in US textbooks. In physics, US textbooks include six types at this level, versus three in Israel.

Representations' Systems Framework

We analysed textbook explanations by systems frameworks: System Dynamics (SD), Structure-Behavior-Function (SBF), and Agent-Based Modeling (ABM). Explanations were coded using seven dimensions: behaviors and properties of components (ABM, SBF), randomness (ABM), interactions between components (ABM, SBF), functions (SBF), heterogeneity of entities (SBF), and stocks and rates (SD). These dimensions helped identify the frameworks in DE explanations (Figure 3).

SD dominates across disciplines with 173 phenomena, while ABM appears in 48 and SBF in 35. In biology, SD is most common, with ABM and SBF appearing less frequently. Chemistry is dominated by SD, with minimal ABM and almost no SBF, especially in Israel. In physics, SD is again prevalent, with ABM more frequent than SBF.

Figure 3. Frequency of System Frameworks (SD, ABM, SBF) Representing DE-related Phenomena Across Disciplines (Biology, Chemistry, Physics) and Countries.



	Biology		Chemistry		Physics	
	US	Israel	US	Israel	US	Israel
SBF	14	10	1	0	8	2
ABM	17	7	3	4	11	6
SD	50	30	17	25	26	25

Discussion

The research is part of an international project focused on developing representations for DE, a central idea in science that describes how stable patterns form in dynamic systems. It examines the representation of DE in high school science curricula and textbooks in the US and Israel, comparing the content across biology, chemistry, and physics. Key objectives include exploring how DE phenomena are presented and represented through various tools such as graphs, illustrations, and computational models, while analysing differences across disciplines and countries. The study also investigates the use of system approaches like System Dynamics (SD), Agent-Based Modeling (ABM), and Structure-Behavior-Function (SBF) in explaining DE phenomena. Findings reveal that DE-related phenomena make up approximately 14% of the curricula, though many are not explicitly defined as DE-related. Significant differences in the curricula were noted, such as the emphasis on evolution in US biology education versus its exclusion in Israel, influenced by social and cultural factors (Plutzer et al., 2020). Students often struggle with understanding DE due to difficulties in connecting microscopic interactions to

macroscopic phenomena (Wilensky & Resnick, 1999; Friedler et al., 1987). Computational models, though scarce in current curricula, are identified as valuable tools for enhancing systemic understanding of DE. The study emphasizes the prevalence of SD for describing quantitative relationships in chemical and physical phenomena, while ABM is more suited for illustrating bottom-up interactions in biology and physics. SBF, primarily used in US biology and chemistry, connects the structure, behavior, and function of systems. The research concludes with recommendations to develop unified representations of DE that are adaptable across disciplines, enhancing consistency and comprehension. Future studies should explore DE's integration with other scientific concepts and its application to additional fields beyond biology, chemistry, and physics. This effort could expand the educational impact of DE by addressing its complexity through universal frameworks that bridge various scientific domains.

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Can Climate Literacy be taught in Special Education in Greece? Possibilities offered by science textbooks in upper high schools

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As we are already reaching the end of the first quarter of the 21st century, one would expect more progress toward addressing climate change issues, especially after almost four decades of discussions. Despite the admittedly many efforts carried out all these years, these have proven rather unsuccessful. A basic tool modern society has at its hands but does not seem to have made good use of, is the cognitive and emotional preparation of students within formal education to face this reality. Although several years have passed since climate issues entered the international debate regarding formal education, there is still an equally important field, Special Education, where no corresponding interest has been shown. A key element of education is the design of modern curricula and the selection of appropriate, up-to-date textbooks to overcome climate change challenges. That said, this study aims to investigate the presence of climate change issues in Greek Special Education high school (grades 10-12) science textbooks based on the recently updated version of the Climate Literacy Guide. Content analysis concerning textual and pictorial materials of three book series, namely Biology, Chemistry, and Physics, was used for this purpose. Results reveal that the textbooks under study contain rather inadequate and fragmented information concerning the eight essential principles and the seventy-six fundamental concepts of the Guide. The conclusions from the present study could help curriculum designers, textbook authors, and climate scientists collaborate toward the inclusion of Climate Change Education topics into national curricula.

Keywords: Climate Literacy, Special Education, High school science textbooks

Introduction

In recent decades, humanity has faced an onslaught of extreme weather events that threaten its survival, the economies of states and households, and the lives and safety of citizens. These unprecedented phenomena occur violently, have duration and intensity, and modern societies seem incapable of preventing them despite their enormous technological development. The latest report of the Intergovernmental Panel on Climate Change (IPCC, 2023) reveals that human activities, mainly through greenhouse gas emissions, have unequivocally caused global warming. This has led to widespread adverse impacts and related losses and damages to nature and people, although adaptation and mitigation strategies have progressed across all sectors and regions. The United Nations Framework Convention on Climate Change is the first official tool of international law that recognises the problem of climate change and its interconnection with anthropogenic greenhouse gas emissions. However, almost four decades after the signing of this and other respective agreements, global greenhouse gas emissions are still rising rapidly.

In this respect, the need for global climate change education was already reflected in the early ’90s (Henderson & Holman, 1993). However, it was realised only at the end of the first decade of the new century with references to socio-constructivist approaches, conceptual change, and experiential learning (Pruneau et al., 2003), and later with the Agenda 2030 Framework, while key terms such as adaptation and mitigation also begun to associate with climate change education (e.g., Pruneau et al., 2010). According to Anderson (2010), climate change education seeks to teach an understanding of the causes and consequences of climate change, its impact,

and appropriate responses; it further fosters attitudes and motivations to make informed decisions and take responsible action.

This is the time when discussions about the necessity of creating a climate-literate citizenry led to a framework based on the experience of a similar effort (the Ocean Literacy campaign) that preceded a few years earlier. This framework, called Climate Literacy, originally consisted of 7 basic principles, supported by a set of 39 fundamental concepts (USGCRP, 2009) and was thoroughly updated based on current research in September 2024, now portraying 8 principles (Table 1) and 76 concepts (USGCRP, 2024). Climate Literacy is defined as the *understanding of how the climate system works, how human actions influence climate, and how climate influences people and other parts of the Earth system* (USGCRP, 2024). UNESCO (2009) describes this framework as an attempt to help people understand the effects of global warming while encouraging the change in attitudes and behaviour needed to take action on climate change.

Table 1. The Essential Principles of the Climate Literacy Guide.

Principle #1	**[How we know]**	Scientists understand the climate system through interdisciplinary observations and modelling
Principle #2	**[Climate change]**	Greenhouse gases shape Earth's climate
Principle #3	**[Causes]**	Burning fossil fuels and other human activities are causing the planet to warm
Principle #4	**[Impacts]**	Rapid warming and other large-scale climate changes threaten human and ecological systems
Principle #5	**[Equity]**	Climate justice is possible if climate actions are equitable
Principle #6	**[Adaptation]**	Humans can adapt social, built, and natural environments to better withstand the impacts of climate change
Principle #7	**[Mitigation]**	Reducing emissions of greenhouse gases from human activities to net zero by 2050 can help limit global warming and climate change impacts
Principle #8	**[Hope & Urgency]**	A liveable and sustainable future for all is possible with rapid, just, and transformational climate action

Although several years have already passed since climate issues entered the international debate and, therefore, became a topic of interest within the boundaries of formal general education, a corresponding interest focusing on Special Education does not seem to have been a similar concern for the experts of the field. UNESCO defines Special Education as the one designed to *facilitate learning by individuals who, for a wide variety of reasons, require additional support and adaptive pedagogical methods to participate and meet learning objectives in an education programme* (UIS, 2012). Even though significant research has been published concerning Special Education and science and/or environmental education, to our knowledge no respective research has been conducted regarding Special Education and climate issues in particular. A key element of education is the design of modern curricula and the selection of appropriate, up-to-date textbooks to overcome climate change challenges. This becomes even more imperative when addressing scientific issues within the framework of Special Education. Tracana et al. (2008) have reported that textbook analysis is an important parameter in implementing national educational objectives at the school level. Therefore, this study attempts to investigate the presence of the Climate Literacy basic principles and fundamental concepts according to the corresponding Guide in Greek Special Education high school science textbooks.

Materials and Methods

The corpus under study comprised three series of reading books, namely *Physics*, *Chemistry*, and *Biology* (Figure 1), all corresponding to compulsory courses in Greek upper high school grades 10-12 (15-18 years old), used in Special Education. Content analysis was selected based on both textual and pictorial material from the corresponding school manuals to evaluate the presence of

climate science issues according to the Climate Literacy Guide. With regard to the presence of climate sciences issues, both the manifest and latent content were examined, referring to both visible and underlying components of each passage of the text (e.g., Downe-Wamboldt, 1992). The unit of analysis and the construction of categories were also considered. Concerning the former, the "theme" was chosen as, according to Krippendorff (2004), thematic excerpts are rich in information and preferable to other kinds of distinctions; in terms of the latter, a deductive coding scheme (Stemler, 2001) was followed, as the 8 essential principles and 76 fundamental concepts of the recently updated Guide (USGCRP, 2024) constituted the categorical context for the respective analyses. In addition to the above, the validity and reliability of the procedure were also ensured.

Figure 1. The Special Education upper high school science textbooks under study.



Results

The present study revealed that although all Climate Literacy principles (CLps) are presented in Special Education upper high school science textbooks, twenty-six of the total seventy-six supporting concepts are lacking (Figure 2), while the existing ones are not entirely addressed, according to the corresponding Guide. Climate Literacy principle 2 referring to the greenhouse gases that shape Earth's climate, CLp 3 regarding the causes, CLp4 providing valuable information about the impact, and CLp7 concerning mitigation strategies are adequately covered in terms of the number of concepts for which information is displayed, and the number of references to these principles reflected in all textbooks (Figure 2). On the contrary, CLp1 referring to the fact that scientists understand the climate system through interdisciplinary observations and modeling, and CLp6 regarding adaptation strategies, seem to be the least representative both in terms of the number of concepts covered and number of references that appear in all science textbooks (Figure 2). In Figure 3 we can easily detect that almost the same Climate Literacy fundamental concepts are recorded in all three studied textbook series, although we observe a remarkable quantitative difference between the Chemistry textbooks on one hand and Physics and Biology textbooks on the other. More specifically, the textbook with the most relevant information, Chemistry, appears with 8 principles, 48 concepts, and 528 references in total,

followed by Biology (8 principles, 30 concepts, and 115 references), and finally Physics (7 principles, 33 concepts, and 55 references) (Figure 4). With regard to the grade level, grade 11 appears to be the richest in information with 8 principles, 48 concepts, and 344 references, followed by grade 10 and grade 12 (Figure 4).

Figure 2. Total number of Climate Literacy fundamental concepts in Special Education upper high school science textbooks.

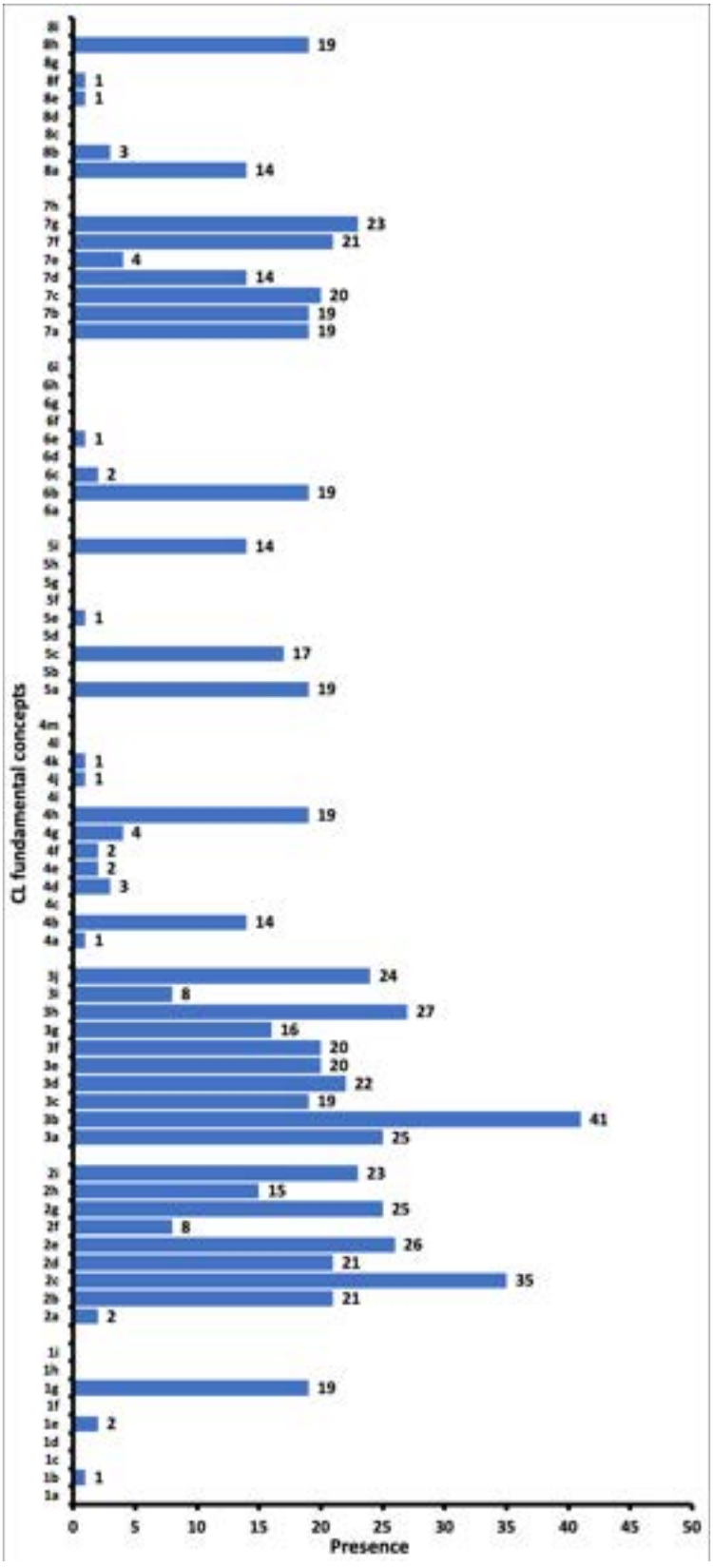


Figure 3. Total number of Climate Literacy fundamental concepts per science textbook.

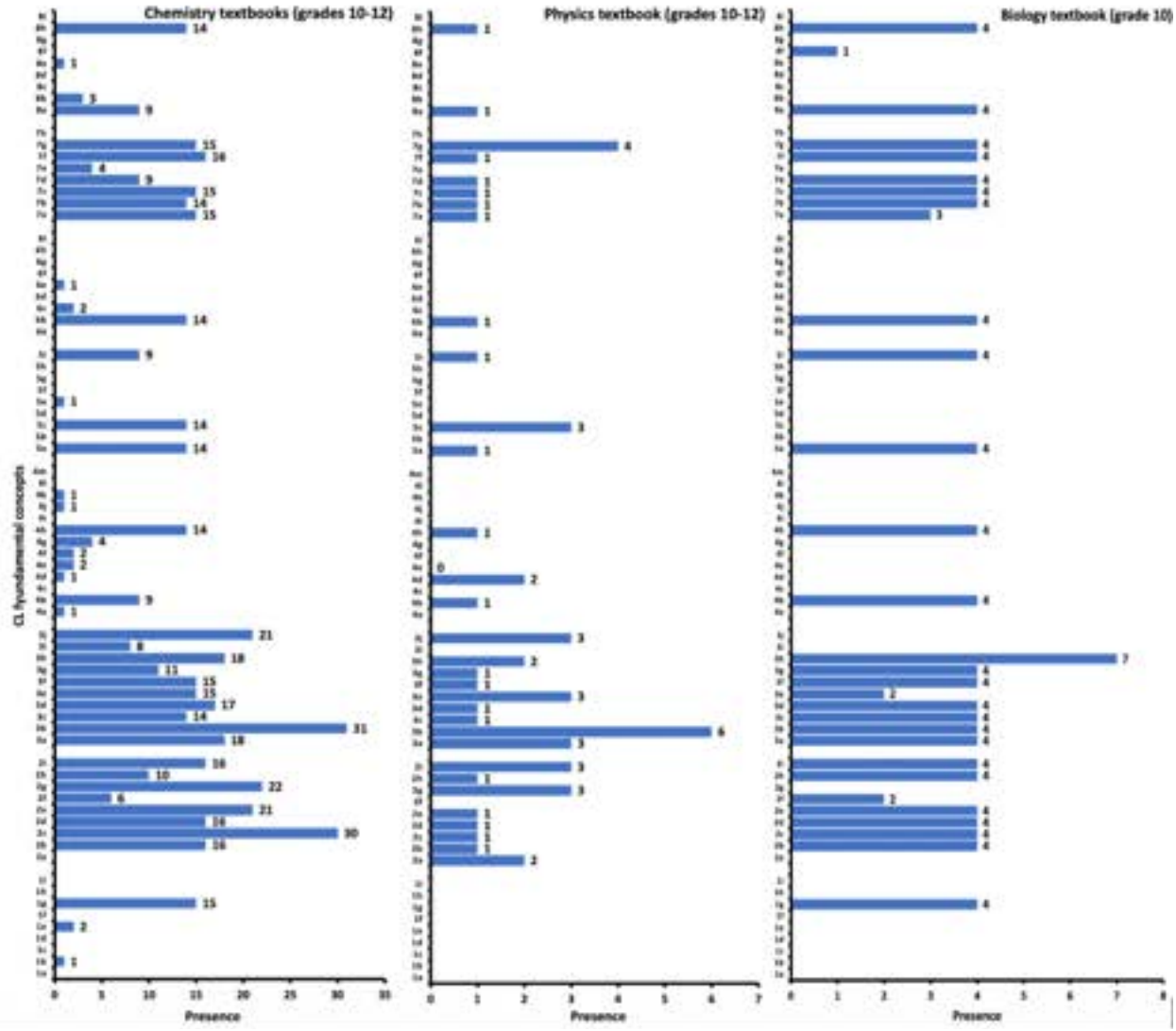
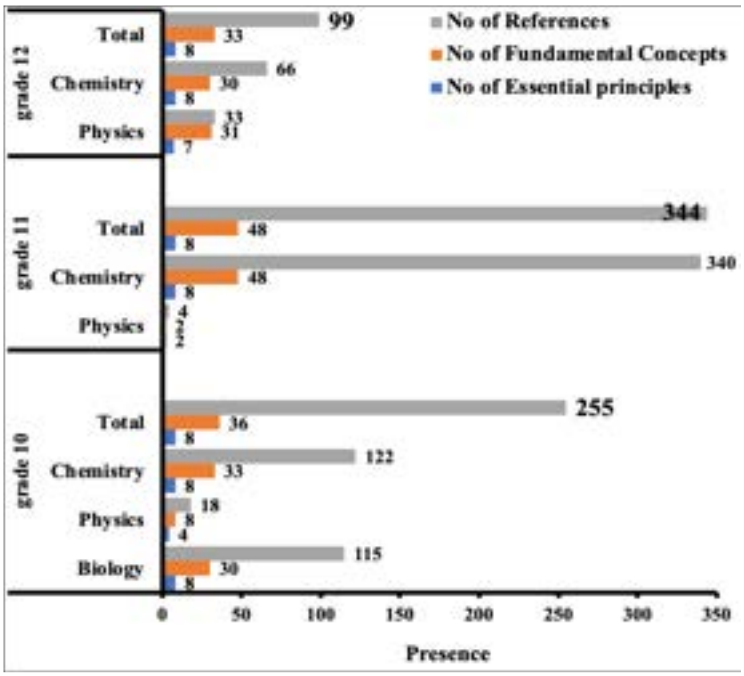


Figure 4. Number of Climate Literacy basic principles, fundamental concepts, and references per grade and science textbook.



Discussion

Content analysis of Greek science textbooks' textual and pictorial material revealed that although all eight essential principles and some aspects of many fundamental concepts of the recently updated Climate Literacy Guide (USGCRP, 2024) are mentioned in the Special Education upper high school (grades 10-12), nevertheless these are only partially covered, making the relevant information rather superficial and fragmentary. Most principles and concepts are found in Chemistry, while grade 11 appears well-stocked in pertinent information. Important issues such as, among others, the distinction between climate and weather, climate variability, exposure of marginalized and low-income populations to climate hazards and associated health problems, climate impact on businesses, governments, and economies, necessary shifts in institutions, behaviours, and values, the demand of huge financial investments in new technologies, infrastructure, and education are missing, making climate change education rather unpromising for upper high school students enrolled in Special Education settings. Furthermore, the existing information seems to be rather inappropriately presented, as the degree of difficulty exceeds the cognitive capabilities of students with special needs.

Although research on climate change education has thrived over the last 15 years, to our knowledge, relevant issues are not currently included in national curricula or school textbooks. As a result, we cannot reliably assess the impact of the Climate Literacy framework on formal education systems worldwide. Moreover, it appears that no scientific interest at all exists in making climate change education more inclusive by incorporating it into Special Education. It seems that either this innovative framework has not been properly communicated, particularly to policymakers, or we have not fully grasped the critical need to introduce this knowledge to modern society. As the USGCRP (2009) elegantly states, only "*a climate literate person understands the essential principles of Earth's climate system, knows how to assess scientifically credible information about climate, communicates about climate and climate change in a meaningful way, and is able to make informed and responsible decisions regarding actions that may affect climate*."

The latest IPCC report (IPCC, 2023) is undeniably clear about the causes of climate change and the anticipated consequences if adaptation and mitigation measures are not implemented immediately. Drawing inspiration from a recent book by Gates (2021), we must achieve something monumental; we need numerous groundbreaking discoveries in science and engineering, we need to reach consensus where it currently does not exist, and we need to design government policies that will accelerate a transition that would not happen otherwise. None of these will be accomplished if we do not make climate change education an integral part of our national education systems, and the Climate Literacy Guide can serve as a solid foundation for student awareness in formal education.

In conclusion, the above mapping could help curriculum designers, textbook writers, classroom teachers, and climate scientists successfully integrate Climate Literacy issues into current educational systems.

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The Science Curriculum as a Vehicle for Climate Change Education: A Cross-Country Project

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Climate Change Education (CCE) is an increasing focus of global curriculum advocacy, as countries come to terms with the future threats posed by the Anthropocene polycrisis and the need for an informed citizenry that can make critically informed and responsible decisions. Given the crucial role of science in monitoring and responding to Anthropogenic Climate Change, the Sciences are of crucial importance to CCE, yet to date education systems have been slow in taking this up. The recent OECD PISA 2025 Science Framework places fresh emphasis on students' critical evaluation of evidence to make informed decisions in relation to socio-ecological challenges, advocating a focus on student decision making, action, and agency. This symposium represents selected explorations in a cross-country project focused on enacting CCE within Science curricula consistent with these ideas. The three explorations map out the potential to productively include CCE in these subjects, through 1) a cross-country survey of teachers' knowledge, practice, and confidence of CCE, 2) a cross-country analysis of the structure and amount of ACC content in middle years textbooks in the science disciplines, and 3) co-design research with a primary school science specialist exploring how best to infuse CCE into a traditional science curriculum across multiple topics. The set of three explorations identify systemic constraints on the infusion of CCE, but provide confidence that the conditions exist with teachers, students, and education system commitments and resources for expansion of science curricula to contribute to CCE.

Keywords: Climate Change Education, Teacher learning, Curriculum

Introduction

We are living in an epoch of human induced Climate Change (CC) (Lee et al., 2023), the 4th industrial revolution (Schwab, 2016), and the 6th mass extinction (Dirzo et al, 2014) - the Anthropocene (Lewis & Maslin, 2015). There are urgent calls for education to focus on developing students' knowledge and agency with respect to the global socio-ecological challenges of CC These issues have been well represented in the fields of *Environmental Education* (EE) and *Education for Sustainable Development* (ESD) for decades, and as the cross-curriculum priorities in a number of countries. Currently, increasing urgency in the scale and global nature of impacts have encouraged the formulation of CCE that better represents the climate science, societal impetus, and social impacts and that integrates more directly with school disciplinary subjects. CCE is different from either EE or ESD (Monroe et al., 2019; White et al., 2024) in referring to key content and concepts associated with the complex interactions of climate science and the social systems that have generated unprecedented and significant impact on all Earth systems (OECD, 2019).

Calls for the development of a systematic CC Education (Academy of Social Sciences in Australia [ASSA], 2023) have slowly been taken up by most systems (Dawson et al., 2022; Roussel et al., 2020), reprising challenges in incorporating Education for Sustainability (EfS) as a core commitment (ASSA, 2023). CCE, while related to EfS, brings new elements of science into focus, as well as enhancing temporal and global spatial dimensions concerned with

interconnected Earth systems. In contemporary scientific research and development, CC related initiatives are increasingly important, identifying interruptions to Earth systems; investigating the interconnections between global systems to build increasingly complex climate models; monitoring temperature and the effects of global temperature rise; designing climate mitigation approaches; developing technologies for the transition to low carbon energy systems; and understanding climate related events (Lee et al., 2023).

The OECD PISA 2025 Science Framework (OECD, 2023) is a transformative document in expanding the remit of science education to prepare students not only to explain and engage in the traditional knowledge building practices of science, but to develop the competency to *research, evaluate and use scientific information for decision making and action*. The strong environmental science agenda has been introduced into the Science Framework, informed by the companion document 'Agency in the Anthropocene' (White et al., 2023; 2024), to further interpret and expand the competencies such that 15-year-olds should be able to:

1. Explain the impact of human interactions with Earth's systems.

2. Make informed decisions to act based on evaluation of diverse sources of evidence and application of creative and systems thinking to regenerate and sustain the environment.

3. Demonstrate hope and respect for diverse perspectives in seeking solutions to socio-ecological crises.

Thus, what has been mainstream in EE and EfS has now been recognised within the science framework as an important aspect of a mainstream science education, going beyond explanation, interpretation and engagement in core science practices to consider science knowledge and practice related to the socio-ecological challenges of the Anthropocene (White et al, 2024).

This paper describes the developing research agenda of a cross-country research project 'Enacting Climate Change Education (ECCE) through representing Scientists' Practice' (ECCE, 2025) that responds to the agenda enabled by the OECD PISA Science Framework 2025. ECCE involved science education researchers from Australia, Finland and Taiwan co-designing teaching and learning sequences that infuse CCE with teachers and with scientists' input into the science curriculum. An emphasis on student knowledge, dispositions and decision making and action leading to student agency as envisaged in 'Agency in the Anthropocene' was the priority. The explorations described are structured to explore the possibilities and potential pathways for the much needed substantial infusion of ACC into the science curriculum (Dawson et al., 2022). The set of three explorations represent preliminary scoping work for the project, which investigate: 1) teacher engagement with ACC; 2) textbook representation of ACC across the three countries, and 3) an Australian example of a Design Based Research approach with teachers to explore the possibility of infusion of CCE into a full year's science curriculum.

Exploration 1: Teacher Knowledge, Practice, And Confidence In CCE: A Cross-Country Comparative Analysis

In any major curriculum reform agenda, teachers are key. This is particularly the case with contexts such as climate science where the complexity of interacting Earth systems are impacted by social priorities and practices resulting in socio-ecological challenges. Not only is the science contemporary and situated, but essential to addressing socio-ecological related crises are the complicated relationships between human behaviour, technologies and environmental degradation. Teachers of science thus need to extend their science knowledge by drawing on contemporary research, but also complex socio-ecological dynamics underpinning. Thus,

teachers, and teacher professional learning is critical to enacting a CCE curriculum in science (Tytler & Freebody, 2023).

Methodology

A Qualtrics online survey was administered to secondary school teachers of Science and Humanities, invited through online invitations through teacher organisation in each country. The questions were translated into the three languages and cross checked by the team. Participant numbers were 67 in Australia, 68 in Finland, and 86 in Taiwan. Survey participants were mostly secondary teachers, mostly teaching science.

The survey consisted of 23 questions of mixed type, focusing on the following aspects of teachers' experience with CCE: knowledge of CC phenomena; perceptions and confidence in relation to CCE; the nature of their CCE practice in terms of the degree of embeddedness, nature of focus; resources and engagement with climate scientists; degree of support; reasons for teaching/not teaching CCE; the nature of outcomes that should drive CCE; the urgency of including CCE in the curriculum.

Analysis

The reliability of the questions was tested using Cronbach's alpha. The results revealed that most of the questions showed high reliabilities (alpha > .90), excluding two questions. Questions with a single sub-item or "yes or no" questions were excluded from calculating Cronbach's alpha. Analysis of the data mainly used descriptive statistics, but cross-country comparisons involved an ANOVA analysis to identify significant differences in response patterns. Extended responses were thematically analysed and verified by team discussion.

Results

Attention to CCE: The responses to the question 'Is CCE embedded in your teaching' yielded a distinct hierarchy in 'yes' responses: Taiwan 86%; Finland 98% and Australia 67%. This reflected curriculum histories in the three countries, with Taiwan including CCE since 2018 and Australia only since 2022 in a limited way. This hierarchy was reflected in many of the question responses.

Knowledge of CCE: Despite the difference in practice, teachers across the three countries expressed strong knowledge of 'the scientific explanations for CC', 'the role of human impacts of CC, and 'the impacts of CC on the environment and on humans', with mean scores in each case above 4.2 on a 5-point scale. Knowledge of 'approaches to CC mitigation at the personal and societal level' were equally strong for Finnish and Taiwanese teachers but significantly lower for Australia ($p=0.004$). Knowledge of 'the way individuals and societies must adapt everyday practices' was strong for Taiwan, but significantly lower for Finland and Australia ($p=0.0001$). The picture of teacher knowledge is thus strong overall, but with significant gaps in responses to CC reflecting curriculum histories.

Confidence in aspects of teaching CC: Teachers across all countries expressed confidence (mostly 4 on the 5-point scale) about a variety of aspects of teaching CC, generally without significant differences, including: 'I welcome learners' questions about C'; 'Although this is a complex topic, I feel prepared to teach it'; 'I know how to effectively address learners' misconceptions related to CC' (slightly lower score); 'I am able to use local and global examples to teach about CC.'

Knowledge of key terms and phenomena: In an exploration of teachers' understanding of terms related to CC (e.g., tipping points, net zero), teachers from the three countries generally expressed

confidence in their knowledge of these terms. There were some differences with Australian teachers, for instance, showing significantly lower confidence in understanding 'Circular economy' than Finnish and Taiwanese teachers.

Outcomes of teaching CC: We asked what the main outcomes were when including CCE in science or humanities. Teachers' responses were diverse, but the key focus was empowering students to make appropriate agentic choices and to act accordingly. Teachers emphasised the urgency of teaching about the climate crises but discussed the importance of hope and positive attitudes. The significance of developing scientific literacy in students was highlighted. One teacher focussed her students proactively: "Agency, voice, the feeling that they can do something about it and making students active contributors in community science."

Resources: Teachers' responses indicated the use of a range of formal and informal resources that include textbooks, online materials, news articles, videos (specifically YouTube), social media and documentaries. Some teachers gave specific examples of websites and resources, others stated broad categories. The Australian teachers were significantly less confident in finding reliable resources for teaching about CC" ($F = 5.9635$, $p = 0.0030$).

Discussion

The survey uncovered patterns in both strength of response across countries, and difference between countries on particular aspects of CCE. Overall, the results are very encouraging in terms of supporting the agenda of widening the scope of the science curriculum in line with the PISA 2025 Science Framework (OECD, 2023) and its companion Agency in the Anthropocene document (White et al., 2023). Teachers generally expressed confidence, not only in their own knowledge in teaching the various dimensions of CC Science, but in engaging with students' perceptions and misconceptions about CC. In terms of outcomes of CCE, they focused on empowering students and on the development of student agency in making responsible decisions concerning climate related challenges.

The findings provide confidence that teachers are generally knowledgeable about and committed to a CCE agenda that focusses on student understandings, attitudes and actions. Teachers' preparedness to probe and negotiate with student perspectives and open discussions that attend to student voice is encouraging for establishing a curriculum agenda in science in line with advocacy of activities and content found in the CCE literature (Monroe et al., 2019; White et al., 2023; Academy of Social Sciences in Australia, 2023).

We interpret the difference between patterns of responses between the three countries through a lens of curriculum politics and national political landscapes. In general, the confidence of teachers, and particularly their access to resources, was strongest in Taiwan and weakest for Australian teachers. In Taiwan, Anthropogenic CC has been included in the core Science and Geography curricula since 2018, and textbooks are officially endorsed only if they reflect this (Taiwan Ministry of Education, 2018). In contrast, Australia only included CC in its curriculum in 2022, with inaction before that determined by a decade of CC Denial politics influenced by fossil fuel interests (Crowley, 2021). Nevertheless, Australian teachers are only recently entering this curriculum space, and their confidence and commitments are encouraging. Finland's in-between position is related to considerable support by the Finnish government promoting ecologically sustainable practices and strengthening learners' climate knowledge and skills (Hilldén et al., 2022).

Exploration 2: Representations Of Anthropogenic CC In Science Textbooks: A Cross-Country Comparative Analysis

In recognition of the importance that resources play in supporting Science teachers to embrace new topics, particularly those representing contemporary science and socio-ecological challenges associated with ACC, we analysed Science and Geography textbooks across the three countries; Australia, Finland and Taiwan. The analysis was framed to ascertain the proportion of the total curriculum in these subjects devoted to CCE, interpreted through the space devoted to ACC topics in each subject as a percentage of total textbook page area.

The research questions for this exploration are: 1) What is the percentage of textbook space devoted to anthropogenic CC in the core Science and Geography subjects across the secondary schooling years, and across subjects, in the three countries? 2) What different themes are represented concerning ACC, and what are their patterns of representation in the different subjects? 3) What can we learn, from this cross-country comparison, about the different ways ACC can be addressed through different subjects and topics? An account of the methodology and findings can be found in Tytler et al. (2025).

Methods

We used the Comparative Case Study (CCS) approach by Bartlett and Vavrus (2016), designed to examine varying contexts and scales. In comparing CCE content in lower secondary school textbooks from three countries, it allowed us to explore how each country addresses CC in their textbooks, considering both similarities and distinct features. We situated the analysis within the particular curricular contexts of each country, and also the wider policy landscape, to generate multidimensional insights into national distinctiveness and shared patterns in CCE across the three countries.

We developed a Framework consisting of a set of code categories and codes that was refined over a series of meetings and a substantive coding exercise by the Taiwanese team. A coding scheme was developed and refined through further comparative discussion. The flowchart of coding steps is shown in Tytler et al. (2025). The relevant inter-rater reliability exceeded 0.75 in each case.

The unit of analysis was a sentence or coherent section of the text, including figures and tables, related to ACC. For each such unit, the percentage of page area relating to particular codes was measured to the nearest 10%, and a running total collected to calculate the percentage of total text area devoted to ACC, and of that, the % area dedicated to each code.

The major coding categories, each of which consisted of multiple codes, were:

- Science and technology ideas (SI)
- Nature of science (NOS)
- Human-environment interactions relevant to CC (H/E)
- CC impacts on humans (CCI)
- Response to CC and environmental threats (SR)
- Principles around sustainable human environments and CC (SHE)
- Suggested activities (Act)

Within each of these categories were a set of distinct codes. The analysis identified the percentage of curriculum space for each of the Sciences, and Geography, dedicated to ACC, and within that the breakdown of coding categories and codes. The results represent a proxy measure of the extent of CCE embedded in each country's Science curriculum.

Information about the curriculum context for each country, including the relationship of textbook design to the formal curriculum, the degree of autonomy allowed for writers and teachers, and the broader CCE policy context, allowed interpretation of findings in terms of curriculum policy.

Findings

The percentage area of text related to anthropogenic CC across the Science and Geography curricula varied between the countries: 2.7% in Taiwan, 1.5% in Finland, and 0.7% in Australia. We identified the following contextual factors affecting these numbers: The explicit inclusion of ACC topics in the Taiwanese curriculum since 2018; the close association of textbooks with the formal curriculum in Taiwan supported by ratification processes; the autonomy of textbook writers, schools and teachers in Finland and Australia with respect to interpreting the curriculum; the existence of significant policy initiatives in Finland supported by resources for CCE inclusion in the curriculum compared to lack of tangible support for a 'Sustainability' cross-curriculum priority in Australia; the existence in Australia over the crucial 10 years prior to 2019 of significant CC denial politics spilling into curriculum 'culture wars'.

In terms of details of CCE representation, analysis showed significant differences in patterns by year level, indicating no agreed progression model for CCE.

Representation in different subjects: There are similarities but also significant differences in representation of CCE across the Science disciplines. The bulk of ACC content is covered by Earth Science and Geography. In Finland, Earth Science is part of the Geography curriculum. There is substantial representation of CCE in each Biology, Chemistry and Physics in at least one country, but considerable variation across the countries. Percentage distribution of anthropogenic CC content by subject discipline can be found as Figure 5 in Tytler et al. (2025). Thus, a case can be made that ACC content can be productively included in each of the disciplines, but this has not been uniformly taken up.

Patterns of code categories across the three countries: The bulk of textbook CCE presence in each country is the SI (Science and Technology Ideas) category representing 32-47% of ACC space. The Nature of Science (NOS) and Principles around Sustainable Human Development (SHE) codes are disappointingly small, particularly given the emphasis on NOS in contemporary science literacy advocacy. Variations from which we can learn include country differences in representation of CCI, SR and HE. Percentage representation of each of the major code categories is depicted as Figure 6 in Tytler et al. (2025).

The analysis reveals patterns in the representation of CCE in Science curricula which are significant for understanding curriculum enactments in this fast-changing field.

The positioning of ACC in the curriculum: The extent of CCE representation is related to the extent of explicit inclusion of ACC topics in the formal Science curriculum, with cross-curricular, interdisciplinary approaches leading to lower levels of representation. However, strong policy initiatives and resourcing are impacting positively in Finland, indicating a degree of political will that is missing in Australia that has compromised curriculum action.

The role of Science disciplinary subjects: Most CCE work is undertaken by Earth Science and Geography, between these accounting for over 60% of ACC content in each country. There was, however, smaller but significant ACC content in each of the Science disciplines that can point a way to greater representation of ACC in Science as advocated by the PISA 2025 Framework.

Widening the science curriculum to include socio-ecological challenges: Current research and curriculum advocacy in CCE focuses not only on knowledge and attitudes but on decision making and responsible action (OECD, 2023; Monroe et al., 2019). We argue that if the Science

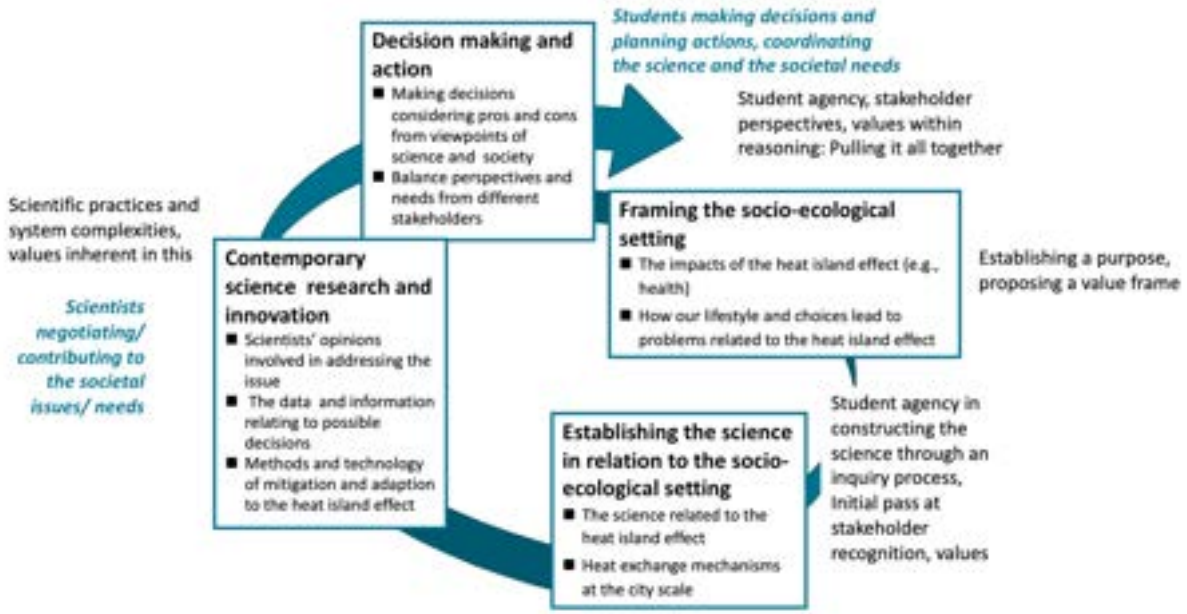
disciplines are to be an important part of CCE, they need to include not only knowledge of systems and effects, but also human-environment interactions around socio-ecological challenges. Patterns of codes show each of these are included in at least some of the texts, giving confidence that Science writers accept this challenge. These cross-country differences present an opportunity to further explore what effective representation of CCE themes might include, as a contribution to advancing our understanding of the dimensions of a quality CCE-rich disciplinary curriculum (Tytler et al., 2025).

Project 3: Developing A Co-Design Model For Infusing CCE Into The Science Curriculum

The central intent of the ECCE project is to work with teachers to develop approaches to infusing CCE into the science curriculum to foster student agency.

Drawing on the experience of the researchers from the three partner countries (Australia, Finland and Taiwan), we developed a learning sequence design model (Figure 1) that leads from a socio-ecological challenge through establishing the required science knowledge, representation of current research, and finally to student consideration of decision making and action in relation to the challenge.

Figure 1: Learning sequence design model with illustrative examples referring to a simulation module on the heat island socio-ecological challenge in Taipei.



While the nature of co-design processes across the countries varies, each of the learning sequences is evaluated against student outcomes in terms of: knowledge (science of CC and human causes, processes for dealing with ACC and impacts); values (eco-justice, hope and resilience); decision-making and action (design approaches, commitment to acting, self-efficacy, engage with civic processes). In drafting sequences, strategies designed to support student agency are prioritised, which involves privileging student idea generation, decision making and action.

This exploration focuses on a particular co-design partnership with a specialist Year 5-6 science teacher in Australia, involving the entire year's science curriculum to infuse ACC related content while attending to the core science curriculum requirements. The research questions we addressed were: 1) What are the affordances and challenges of infusing CCE into the science curriculum? 2) What is the experience of a primary teacher of science, of co-designing CCE- focused curriculum sequences? 3) What student outcomes can be discerned from a year-long CCE infused science curriculum?

Methodology

In the project we utilise Design Based Research (Plomp & Nieveen, 2013) with a strong co-design approach, to generate draft classroom sequences that are negotiated with the teacher, and then iteratively refined both during the sequence and across sequences. Design research reflects a pragmatist epistemology by which theory development is grounded in interrogation of practice (Cobb et al., 2003).

To develop the draft Year 5-6 sequences, the research team drew on scientific expertise regarding, for instance, energy transition research, bushfire disaster expertise, and research into bees and environmental threats. For each topic the team consulted with the teacher concerning ACC links.

Evaluation of the sequences during the design cycle drew on: interviews with the teacher and students following each sequence; pre-and post-sequence written assessments; field notes and video capture of classroom interactions; capture of student work samples; and notes taken during planning and review sessions within the team and with the teacher.

Results

We discuss the results in the order of the research questions: the experience of infusing CCE into science curricular topics; the experience of the teacher in emphasising ACC; and student outcomes from interview and survey data.

Infusing CCE into the science curriculum: For the different science topics represented in the Victorian (Australia) curriculum the school follows, the possibility of infusing CCE varied considerably. However, it proved possible to use ACC as a significant context for teaching science content within each of the eight sequences we worked with across the two-year levels. Table 1 provides examples of some of the inclusions of CCE into these science topics, together with activities designed to support student decision making and agency.

Table 1: Examples of CCE infusion into traditional science topics

Science topic	CCE content based in science research	Activities focused on student agency
Energy transformation	The nature of transformations in renewable energy sources and electrification in the energy transition. Hydrogen energy research, electrolysis and social licence.	Development of scenario around fuel cell conversion of a local bus line. Future energy scenario building.
Astronomy	Earth as a Cinderella planet and the greenhouse effect. Investigation of satellite climate monitoring data.	Students investigating patterns in online satellite data.
Biodiversity	Sequence on bees, informed by bee research expertise, and focusing on hive collapse threats and biodiversity loss.	Role play focused on socially acute question of managing varroa mite spread.
Light and vision	Electromagnetic spectrum and infrared. Use of infrared cameras to identify heat loss points in school buildings.	Development of design proposals to the school to improve energy efficiency.

The experience of the teacher in co-designing sequences: The teacher, Maja, is a science specialist leading three classes each of Years 5 and 6 for science, for a one-hour lesson each week.

The repeat classes allowed us to informally discuss a lesson prior to the repeat. Our negotiations with Maja often concerned clarifying the science or providing background to the relevant socio-ecological issues, while she provided advice on how to frame activities, and on structure and timing. Maja has a strong sense of how to engage students in discussion and was increasingly confident with and dedicated to both emphasising students having a voice on the science and socio-ecological issue, and in interacting with each other in developing explanations and arguing for positions. Her advice was particularly strong on matters of students discussing decisions and actions that could influence school policy.

Student outcomes: Student focus group interviews were held at the end of each sequence and a review interview at the end of the year. Students generally were very positive about the science they were doing, engaged with science ideas, and expressed a commitment to the need to act on CC and sustainability more generally. Assessment results at the end of each sequence generally showed strong growth in knowledge of science concepts. In an end of year survey, over 80% expressed confidence to explain key features of ACC, and a clear distinction between climate and weather.

One question on the survey distinguished between interest and importance of three types of activity: design activities denoting action; doing practical activities; learning about science phenomena; and learning about implications of CC for the future. Each was given a score from 0 (not at all interesting/important) to 3 (very interesting/important).

The results show a uniform level of 'interesting' for these activities, but the 'importance' level is strikingly higher for learning about implications of CC for the future (2.7) and design activities denoting action (2.5) compared to learning content or doing practical activities (1.5-2.2). If this finding is repeated more generally, it has significant implications for the expansion of the science curriculum to include student decision making and action, and consideration of socio-ecological challenges as advocated in the OECD PISA Science Framework 2025 (OECD, 2023).

Discussion And Conclusion

These three explorations were part of the initial phase of the ECCE cross country project. Research is ongoing concerning the development of learning sequences and approaches to CCE that foreground critical understandings, systems thinking and student agency related to climate impacted futures and regenerative learning. The incorporation of contemporary science research in a co-design process is central to the project.

The explorations described in this paper demonstrate the viability of introducing education system responses to CC challenges. The first exploration demonstrates teacher confidence in climate science and in developing pedagogies related to not only science knowledge but also focused on affective and perceptual outcomes and student agency. The second exploration identifies substantive differences in the amount of CCE content in the three countries which are related to curriculum policy and contextual system influences but demonstrates that this rich array of CCE ideas are represented across the Science disciplines and Geography in at least some countries, providing confidence that CCE can be productively and richly represented in the science curriculum. The research identified particular roles for the different disciplines in representing CCE, and the analysis promises to yield useful data to inform the design of a systematic approach to CCE in the sciences.

The third exploration identifies a variety of ways CCE can be included in diverse science topics to provide substantive engagement with learning and agency. Teacher commitments and positive student outcomes demonstrate that the science curriculum can be enriched through infusion of CCE in ways that benefit both teachers and students. The exploration also demonstrates the power

of a co-design approach to CCE that involves contemporary scientists and their research, teachers, and in some cases students. We continue to refine our understandings and approaches, drawing on insights based in our cross-national collaboration to sharpen understandings of the contextual factors that frame possibilities of innovation in this CCE.

Acknowledgement

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Part 14 / Strand 14

Evaluation and Assessment In Teaching and Learning

Co-editors: *Jesper Bruun, Regula Grob & Olia Tsividanidou*

Part 14 / Strand 14 Evaluation And Assessment in Teaching and Learning

Development, validation and use of standardised tests; instruments for measuring attitudes, interests, beliefs, self-efficacy, science process skills and conceptual understandings; authentic assessment, formative assessment, summative assessment, as well as approaches to assessment, monitoring student learning and implications for teaching. Includes international comparison studies such as TIMSS and PISA.

Sub-themes:

1) Development and Validation of Science Assessment Instruments
2) Formative Assessment Strategies in Science Education
3) Summative Assessment Practices in Science Classrooms
4) Implications of International Assessments (e.g., TIMSS, PISA) on Science Education
5) Assessing Student Attitudes and Beliefs in Science

Contents

Strand 14: Evaluation And Assessment In Teaching And Learning 1275
Assessment of Analogical Activities for Learning an Immune System Model 1276
Enhancing Climate Literacy Through Assessment Activities Designed by Pre-Service Primary Teachers 1285

Strand 14: Evaluation And Assessment In Teaching And Learning

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Introduction

Evaluation and assessment are integral in contemporary Science Education. Together, they provide evidence that informs educational decision-making at multiple levels, from monitoring student learning to improving classroom practice and educational programmes. Within this broader landscape, assessment increasingly serves as a means of supporting learning, informing teaching, and facilitating the development of complex scientific competencies. As Science Education expands its focus towards modelling, systems thinking, sustainability, and other higher-order capabilities, assessment practices must also evolve to capture these multidimensional forms of learning. Increasing attention has been given to assessment approaches that make students' thinking visible, support learning throughout the educational process, and provide evidence of students' conceptual understanding and broader scientific competencies. The two contributions included in this strand illustrate this shift particularly well. Although they address different educational contexts and scientific domains, both investigate assessment as an integral component of learning. They demonstrate how carefully designed assessment tasks can reveal learners' reasoning, inform instructional decisions, and support the development of sophisticated scientific competencies.

Two themes connect the two contributions. The first theme is that assessing a complex competence begins with decomposition. Gómiz-Aragón and colleagues make secondary students' analogical reasoning assessable by resolving it into five operations, each rated on a four-level scale. Botzaki and Stavrou analyse how pre-service primary teachers design formative assessment by coding both the competency objectives the teachers target and the formative-assessment elements they deploy. In each study, the category system is the instrument through which competence is made visible.

The second theme has to do with the difficulty of reflection. In both studies the generative, evidence-gathering steps are handled competently, while the reflective moves are handled less surely. The students readily characterise the target and map similarities, but falter when asked to weigh the analogy's limitations and utility. The pre-service teachers elicit and even interpret evidence in varied ways, yet plan feedback, and opportunities for students to act on it, far less often, leaving the formative cycle unclosed.

Read together, the two studies span both sides of assessment—the student being assessed and the teacher learning to assess. We hope the ideas presented here prompt continued attention to how assessment can guide learning in a time when science education is increasingly concerned with sustainability and complex competencies.

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Assessment of Analogical Activities for Learning an Immune System Model

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This study investigates the use of analogies in secondary-school immunology teaching, comparing the immune system to a security system within a modelling framework. A total of 181 students participated in activities focused on five analogical operations: target characterisation, mapping of similarities, use of analogical language, identification of limitations, and recognition of utility. Regarding the first research question (RQ1), high levels of performance were observed in target characterisation and the mapping of similarities, whereas students encountered difficulties in using analogical language and identifying limitations. The perceived utility of the analogies varied considerably. For the second research question (RQ2), correlation and principal component analyses indicated that all five indicators contributed to a common construct of analogical performance. Nevertheless, the identification of limitations and the perceived utility showed weaker relationships with this construct. These findings suggest that constructing and reflecting upon analogies fosters both understanding of the immunity model and the development of skills in constructing and evaluating scientific models.

Keywords: Analogies in Science; Secondary Education; Teaching Processes

Introduction

Teaching immunology is essential for educating citizens capable of understanding information related to this field and making informed decisions that enhance their quality of life (Mixter et al., 2023). However, learning how the immune system functions presents significant challenges due to the large number of concepts involved and the multiple scales that must be considered, ranging from the molecular to the systemic and even the social level (Haidaris & Frelinger, 2019). Consequently, it is necessary to implement teaching strategies that facilitate the comprehension of these complex topics.

A particularly effective approach to addressing this challenge is through the use of analogies. Analogies act as mediators between the observable world and scientific models (Marzabal et al., 2024), allowing familiar phenomena to be related to complex scientific concepts. In this way, they support the construction of mental models (Clement, 2000) and assist in the creation, revision, and validation of scientific models (Gilbert & Justi, 2016). Within this context, analogies constitute a valuable resource for modelling-based approaches, as they enhance the understanding of school-level scientific models and promote engagement with the modelling process itself (Oliva & Aragón-Méndez, 2009).

This work forms part of a broader study analysing how students construct models of immunity using an analogy based on a security system. Specifically, the aim of the present study is to assess students' performance in analogical activities, thereby contributing to a better understanding of the role of analogies in modelling and how they can facilitate the comprehension of complex concepts in immunology.

Theoretical Framework

In science education, the use of models as learning objects and modelling as a scientific practice is well established. School-based models arise from the didactic transposition of scientific models, being simplified, restructured, and adapted to suit students' characteristics and the educational context (Coll et al., 2005; Treagust et al., 2002). Modelling, understood as the construction of models in the classroom, provides opportunities for students to engage in school-based scientific practices and plays an important role in their scientific development.

Analogies constitute a particular type of model, as each involves an underlying abstract representation that gives rise to the *analogy model*. This second-order model synthesises the relational structure between the *target* (what is to be explained) and the *analogue* (the known). Analogies are fundamental tools for teaching complex concepts, as they facilitate the understanding of unfamiliar ideas by relating them to familiar concepts that share similar structure or function (Gilbert & Justi, 2016; Tise et al., 2023). Traditionally, analogies have been used in science teaching as illustrative resources to explain isolated concepts. However, their more effective use requires articulating multiple ideas and relationships, thereby fostering the construction of structured and interconnected knowledge and avoiding fragmented or superficial learning.

Analogical reasoning represents a system of relational thinking based on identifying structural similarities and is considered one of the cognitive foundations of higher-order thinking (Eriksson et al., 2024; Richland & Simms, 2015). Its development promotes knowledge transfer and the construction of conceptual models (Coll et al., 2005; Gray & Holyoak, 2021). Through this process, students generate abstract conceptions from similarities between phenomena, supporting the understanding, application, and reconstruction of scientific models (Gilbert & Justi, 2016). Furthermore, analogies facilitate the practice and acquisition of scientific language, assisting students in articulating and explaining abstract concepts (Eriksson et al., 2024).

The approach based on identifying structural patterns across different domains is enhanced through modelling practices, which enable the generation of explanations, predictions, and inferences about the phenomena under study (Mozzer & Justi, 2018). In this process, students must assess the correspondences between the analogy and the scientific model, evaluating its validity and utility, and recognising when an analogy is appropriate and how to use it effectively (Petchey et al., 2023). Analogical thinking thus stimulates the construction, use, and evaluation of scientific models, while also fostering the acquisition of skills and epistemological perspectives essential to science and modelling (Oliva & Aragón-Méndez, 2017). The relationship between analogical thinking and modelling is bidirectional: constructing analogies involves, to some extent, building models in a domain familiar to students, while engaging in modelling processes enriches the use and meaning of analogies, promoting verbalisation, argumentation, and metacognitive reflection (Aragón-Méndez et al., 2014; Mozzer et al., 2011).

Thus, analogical reasoning, enhanced by modelling practices, not only contributes to the understanding of complex scientific concepts but also fosters advanced cognitive skills and competencies associated with knowledge construction, critical thinking, and scientific creativity (Zorlu & Zorlu, 2022).

For analogies to be effective in the classroom, careful planning is required, taking into account students' prior knowledge and potential risks of misunderstanding (Petchey et al., 2023). Teaching models such as *Teaching With Analogies* (TWA) by Glynn (1991) provide a structured framework to guide learning through analogies. The TWA model comprises six stages: (1) presentation of the target concept; (2) introduction of the analogue and activation of students'

creativity. (3) identification of relevant features in the analogue that show similarity with the target. (4) mapping of similarities and analysis of the compared systems. (5) drawing conclusions, generalising, and formulating hypotheses. (6) establishing the limits of the analogy and critically evaluating its relevance. This approach ensures effective knowledge transfer and promotes active student engagement, as students construct and refine their own analogies rather than receiving information passively (Saleem & Akbar, 2024).

Research in science education has explored, for decades, the cognitive processes involved in analogical reasoning, strategies for teaching with analogies, and factors affecting their effectiveness (Marrero & González, 2023). Analysing analogies created by students can reveal their conceptual understanding and reasoning processes (Tise et al., 2023). Given the multidimensionality of this process, student performance must be assessed using multiple indicators.

Nevertheless, questions remain regarding how to assess students' performance in analogy construction. Therefore, the present study addresses the following research questions:

RQ1: How does students' performance in constructing the immune system analogy vary across different performance indicators?

RQ2: To what extent do these indicators converge and form part of a single construct?

Research Design

Didactic Context

The study involved 181 students aged 14–15 (3rd year of secondary education) from two public schools in Spain. It was embedded in a teaching–learning sequence based on modelling. In this sequence, a security system analogy was employed to facilitate the learning of the immunity and vaccination model at the microscopic level, with a focus on the cellular processes of the immune system.

In immunology teaching, the defence or warfare system analogy is commonly used to represent the immune system (cf. Niebert et al., 2012). The security system is an appropriate analogue due to functional similarities: both detect threats, respond to them, and store information to prevent future attacks. To reinforce the analogy, a silent animation adapted from Bryce (2018) was used. In this animation, pathogens were represented as criminals and immune cells as security agents. Databases and emergency services were also included to strengthen functional correspondences. The absence of audio allowed students to interpret the animation with teacher guidance, promoting interaction, dialogue, and active model construction.

Two activities related to the analogy were analysed: its construction and metacognitive reflection on the analogical model.

In the first activity, students constructed the analogy in two steps. First, they mapped the similarities between the target (immune system) and the analogue (security system). Second, they drew conclusions regarding the characteristics of the target. The analysis focused on the language used, distinguishing analogies from metaphors. Analogies establish a systematic correspondence between the two domains, whereas metaphors transfer meaning from the source to the target (Gilbert & Justi, 2016).

The analogy was interpreted based on Gentner's (1982) structural mapping theory. According to this theory, students establish systematic correspondences between objects in the analogue domain (criminals, agents, databases) and the target domain (pathogens, leukocytes, immunological memory). These correspondences are based on the functional relationships

connecting the two domains. This approach preserves coherent systems of relations and prioritises higher-order structural connections, facilitating the construction of mental models of the immune system and enabling understanding of complex processes beyond the superficial attributes of the elements. Students worked individually with an incomplete analogy. They were required to identify correspondences and relationships between the security system and the immune system.

The second activity focused on fostering students' metacognition regarding the analogical model. Students reflected on the model's usefulness for understanding immune system mechanisms and its limitations. This promoted critical evaluation of the analogical model itself. Guiding questions included: *To what extent does the analogical model allow understanding of how the immune system functions? What are the limitations of the model? To what extent can immune cells be compared to human agents in a security system?*

The aim was for students to understand that scientific models are approximate representations of reality. Models have limitations, and a single phenomenon can be explained using different models. Furthermore, participating in the reconstruction and evaluation of the analogical model allows students to gain a deeper understanding of their own learning process. It also supports the development of competencies related to modelling, analogical thinking, and metacognitive reflection (Gray & Holyoak, 2021).

Overall, students were expected to engage in five analogical operations. Three of these correspond to the TWA model: identifying relevant features of the target, mapping similarities, and indicating the limitations of the analogy. Two additional operations were included: the use of analogical language and metacognitive processes related to the analogy's usefulness in learning the immunity and vaccination model.

Analysis Method

With respect to the five analogical operations identified in the activities—characterisation of the attributes of the target domain, mapping of similarities between the analogue and the target, use of analogical language, identification of the analogy's limitations, and recognition of the model's usefulness for learning—four performance categories were established. These categories allowed the assessment of students' levels of understanding and application (Table 1). The categorisation system was agreed upon through inter-rater consensus to ensure consistency in the classification of responses. Inter-rater reliability was verified using Cohen's kappa coefficient, appropriate for ordinal categorical variables, thereby ensuring consistent classification of students' responses.

Table 1. Category system for performance in analogical activities.

Indicator	Category 1	Category 2	Category 3	Category 4
Target (T). Characterization of the target domain attributes	No correspondence with model elements.	Names immune elements or mechanisms but without description.	Describes immune elements or mechanisms but without naming them.	Fully characterizes immune elements or mechanisms.
Similarities (S). Mapping similarities	No similarities established.	Inadequately established.	Correct but incomplete mapping.	Fully accurate mapping.
Language (A). Use of analogical language	No comparative structures used.	Simple comparative structures.	Metaphorical language without full analogical comparison.	Fully adequate comparative structures.
Limitations (L). Identification of analogy limitations	No limitations identified.	Superficial or unspecific limitations.	Structural limitations identified.	Functional limitations identified.
Utility (U). Recognition of the utility of the analogy for learning the model	No assessment of utility.	Negative assessment.	Both positive and negative assessment.	Positive assessment.

To address RQ1, a descriptive analysis was conducted. The frequency distribution for each category was calculated for each operation, with the aim of identifying patterns and trends in students' responses.

Subsequently, to address RQ2, the relationships between the different indicators were analysed. Kendall's tau-b coefficient, suitable for ordinal variables, was employed. Additionally, a categorical principal component analysis was carried out, allowing exploration of whether the different indicators converge into a single construct of analogical performance.

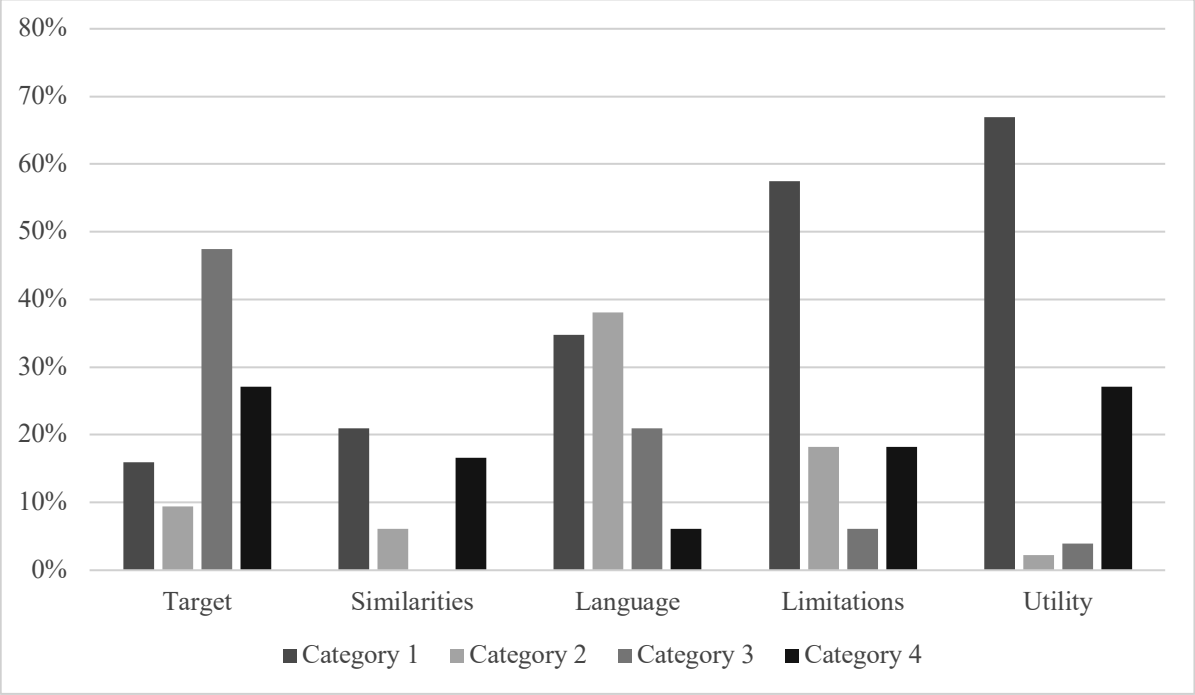
All analyses were performed using IBM SPSS Statistics v.29. This procedure ensured the validity and reliability of the results and provided a robust framework for interpreting students' performance in the analogical activities.

Results

Assessment Of Performance In The Construction Of The Analogy

In response to RQ1, which examined students' performance in constructing the immune system analogy, Figure 1 presents the frequency distribution of performance levels across the five analogical activities.

Figure 1. Patterns in performance on analogical activities



The highest levels of performance were observed in the mapping of similarities and in the use of analogical language, whereas identification of limitations emerged as the weakest area, with many students failing to reflect on the boundaries of the analogical model.

By contrast, recognition of the model's usefulness exhibited marked polarisation: 27.1 % of students positively valued the effectiveness of the analogy for understanding the model, while the majority, with few exceptions, did not perceive its applicability. This pattern indicates a limited degree of reflection on the model's usefulness.

Table 2 presents representative examples of students' responses across the different categories for the five indicators of the analogical operations. Reference responses correspond to the expected answers for each indicator, while the subsequent columns display actual student responses, selected to illustrate performance patterns and the difficulties observed.

Table 2. Representative Examples of Student Responses

Indicator	Categorised examples from student portfolios
Target	Reference: Immunological memory allows a faster and more effective secondary response upon a new infection by the same pathogen. Category T1: Antibodies detect the microorganism and reject it Category T2: Having fought that pathogen, they are prepared for another attack Category T3: Lymphocytes remember the pathogen for when it returns and know how to eliminate it quickly. Category T4: Immunological memory allows lymphocytes to produce specific antibodies, so that if a second encounter occurs, they neutralise it faster.
Similarities	Reference: In both systems, there are elements (phagocytes and riot police) capable of stopping threats (pathogens and criminals). Category S1: The systems act like a threat. Category S2: Both have transport. Category S3: They try to eliminate the threat. Category S4: In both cases, responses are general and rapid.
Language	Reference: Just as different security agents protect populations from various criminals, white blood cells are responsible for protecting the organism from infections. Category A1: For identifying. Category A2: Both defend the place. Category A3: Both systems have elements that watch and inspect for threats. Category A4: Both systems have mechanisms that help detect and eliminate threats.
Limitations	Category L1: It explains very well how the immune system works. Category L2: The immune system can be compared with other systems; although similar, each has its own characteristics. Category L3: The police model and the immune system are similar but differ in important aspects: a single microorganism can cause an infection, whereas a single criminal does not represent a great threat; microorganisms act independently, without a leader. Category L4: The model is very useful but cannot literally represent reality: we will not see phagocytes fighting with weapons. The comparison has limits between the biological and the social or ethical domains.
Utility	Category U1: Knowing the terms and having learned a bit more about the topic, I can understand the model and why many things work as they do. Without prior knowledge, I would not have understood anything, as the terms are not fully explained. Category U2: The model does not explain the order in which different types of immune cells act. Category U3: Models are essential to understand reality, but they must be updated with new discoveries, as they do not reproduce it completely. Category U4: The analogy facilitates understanding by relating the immune system to something familiar, although its abstract and non-visible nature may hinder comprehension.

Note. The students' original responses were in Spanish. The examples presented in this table have been translated into English for clarity and consistency.

Convergence Of Indicators

In response to RQ2, Table 3 presents the correlation matrix calculated using Kendall's tau-b coefficient. The Target and Similarities indicators exhibit the strongest relationship among all pairs of variables. The Language indicator shows significant correlations with all other variables, although these are of smaller magnitude compared with Target and Similarities. The Limitations and Utility indicators display weaker correlations, yet they remain statistically significant. This suggests that these dimensions are less directly related to performance in constructing the analogy.

Table 3. Kendall's tau-b correlation matrix.

	Target	Similarities	Language	Limitations	Utility
Target	1,000				
Similarities	0,616***	1,000			
Language	0,434***	0,569***	1,000		
Limitations	0,336***	0,339***	0,139*	1,000	
Utility	0,359***	0,303***	0,183**	0,229***	1,000

* p < .05; ** p < .01; *** p < .001

Finally, a categorical principal component analysis for ordinal variables was performed (Table 4). This analysis revealed a single-factor solution explaining 54.1 % of the variance. This indicates that all five indicators contribute to a common construct, despite differing levels of difficulty and assessment methods. The extracted factor is particularly associated with the characterisation of the target domain and the mapping of similarities. In contrast, the identification of limitations and the evaluation of utility are more weakly connected to the other indicators.

Table 4. Factor loadings from nonlinear principal component analysis.

	Factor 1
Target	0,867
Similarities	0,886
Language	0,736
Limitations	0,583
Utility	0,538

Discussion, Conclusions, and Implications

Although the literature provides extensive exploration of the use of analogies as a teaching resource in science education, few studies have assessed students' performance in analogy-based activities. This study seeks to contribute to this area. The results indicate that the analogical operations involved in an activity comparing the immune system to a security system, designed according to the TWA model, allow for a comprehensive evaluation of students' performance in completing these tasks.

Students achieved medium to high performance in characterising the attributes of the immune system and in mapping similarities with a security system. However, their performance in using analogical language was lower, possibly due to a general tendency towards laxity in written expression (Archila, 2015).

Difficulties were also observed in analysing the limitations of the analogy, suggesting that this task is more complex than identifying similarities. This complexity relates to the potential of analogies to promote critical thinking, as learning occurs not only by establishing correspondences but also by questioning them and recognising their boundaries (Heywood, 2002; Haglund, 2013). Therefore, providing scaffolding to support the identification of analogy limitations could further enhance students' critical capacity. In this process, analogical reasoning facilitates higher-order thinking, such as the evaluation of ideas and the generation of inferences (Richland & Simms, 2015; Zorlu & Zorlu, 2022).

Although students often noted the analogy's usefulness for learning about immunity, this perception was not clearly reflected in the assessment instruments. When asked about the analogy's usefulness for understanding the immune system model, many students merely used the analogy to demonstrate conceptual understanding, without explicitly indicating whether it had been helpful. This ambiguity suggests a limitation in the formulation of the question.

For future implementations, rather than posing the open question, "To what extent does the analogical model allow you to understand how the immune system works?", it may be useful to reword the question and provide prompts to guide reasoning, such as: "Does the analogy allow you to explain what happens when a pathogen enters the body?" or "Can it be used to predict what would happen if another type of substance were introduced?"

Statistical analysis suggests an underlying factor accounting for students' performance in reconstructing the immune system–security system analogy. This factor may reflect the impact of the activities on developing analogical thinking, linking analogical use with modelling

competencies. Both share cognitive operations –such as identifying structural correspondences, drawing inferences, and evaluating representations– that support model construction and revision (Aragón-Méndez & Oliva, 2020; Justi & Gilbert, 2002). This aligns with Lin and Chao (2024), who define analogical modelling competence as the ability to use analogical reasoning to construct models, integrating cognitive, metacognitive, and behavioural aspects. Classroom use of analogies fosters this competence by offering opportunities to construct and evaluate models.

In line with this, the findings of the present study suggest that students' performance in reconstructing the immune system analogy may reflect not only progress in understanding the immunity and vaccination model but also advancement in their competence to construct and revise scientific models. This hypothesis will be explored further in future research.

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Enhancing Climate Literacy Through Assessment Activities Designed by Pre-Service Primary Teachers

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Addressing Climate Change (CC) challenges requires fostering climate-literate students by developing CC competencies, which can be strengthened through integrated assessment in CC teaching. However, a significant lack of guidance on assessing CC competencies highlights the need for meaningful support to teachers in effectively implementing assessment strategies. The present study examines how nineteen pre-service primary teachers design and develop activities to assess CC competencies. Conducted in two phases, the study first introduced participants to key CC concepts, aspects of climate literacy, and assessment principles. Subsequently, they designed and developed CC teaching scenarios, with a particular emphasis on integrating assessment dimension to foster climate literacy among students.

The findings shed light on the pre-service primary teachers' choices regarding the CC competencies that they aim to foster through their scenarios and the structure of formative assessment elements they employ for assessing these competencies. In more detail, they place particular emphasis on assessing Systems Thinking. Additionally, although participants develop their activities to elicit evidence of students' progress, their feedback practices remain limited, indicating a gap in their formative assessment design. Thus, these findings stress the importance of enhancing assessment practices in teacher education to foster climate literacy.

Keywords: Formative Assessment, Pre-Service Teacher Education, Sustainability

Introduction

Climate Change (CC) is one of the most crucial environmental challenges, mainly caused by anthropogenic activities that harm the environment, affecting multiple aspects of human life (IPCC, 2023). Addressing CC issues requires the preparation of citizens, capable of mitigating the impacts of CC and partially adapting to them. CC education needs to foster climate literacy in students by developing CC competencies - a combination of knowledge, skills, and attitudes (Bianchi et al., 2022). Various frameworks were developed to define the necessary competencies, with a general focus on sustainability, as climate change is inherently part of the broader domain of sustainability. Widely recognized frameworks include Wiek et al. (2011) and the European GreenComp framework (Bianchi et al., 2022), identifying competencies such as systems thinking, futures thinking, and action-taking. Nevertheless, to address key aspects of climate literacy more effectively, recent efforts focus on defining CC competencies using broader sustainability frameworks, such as that of Taurinen et al. (2024).

In this context, achieving the complex goal of developing CC competencies requires contemporary teaching approaches emphasizing active learning (UNESCO, 2017). Such approaches view teaching and assessment as interconnected processes that together enhance student learning (Harris et al., 2019). Accordingly, focusing solely on the final outcome and knowledge acquisition, as is common in traditional assessment methods (e.g., summative assessment), is insufficient to capture the complexity of CC competencies (Annelin & Boström, 2022; Redman et al., 2021). Thus, the assessment of CC competencies requires methods that focus on the whole learning process and provide feedback (Grangeat et al., 2021), such as formative assessment (Annelin & Boström, 2022). The implementation of formative assessment in classroom contexts is based on five key elements: a. setting and sharing with students clear learning objectives and assessment criteria; b. eliciting information from students; c. interpreting

the elicited information; d. providing constructive feedback; and e. creating opportunities for students to apply feedback. These five elements form a cyclical process that supports ongoing learning (e.g., Dini et al., 2020; Grob et al., 2019; Black & Wiliam, 2018; Haug & Ødegaard, 2015).

Nevertheless, teachers face challenges when integrating assessment into their teaching, especially when dealing with multidimensional learning goals, such as the development of competencies (Grangeat et al., 2021). These challenges vary across the steps of the formative assessment cycle, as each step involves different teacher decisions and practices. First of all, teachers tend to focus mainly on assessing knowledge-related objectives rather than students' skills or attitudes (Ropohl & Rönnebeck, 2019; Cisterna & Gotwals, 2018;). In addition, although the literature highlights the importance of co-designing learning goals with students, teachers often avoid setting learning goals collaboratively or explicitly sharing them with students (Cisterna & Gotwals, 2018). Another challenge concerns the elicitation of evidence, in order to assess students' performance and progress in relation to the learning objectives. In particular, when the learning objectives refer to competency development, assessing the conceptual knowledge is not sufficient. Instead, teachers need evidence of students' thinking and reasoning, as well as their skills and attitudes (Grangeat et al., 2021). Thus, a wide variety of evidence is required in order to build a more holistic picture of students' progress (Grob et al., 2021; Cisterna & Gotwals, 2018). Besides the elicitation of evidence, teachers - especially pre-service teachers - often face difficulties during the interpretation of the collected evidence. Particularly, they tend to interpret the elicited information more superficially (Ropohl & Rönnebeck, 2019), either because they do not consistently connect it to learning objectives or because they do not examine in depth how students understand, reason, and argue. This, in turn, limits their ability to identify students' actual learning needs (Ropohl & Rönnebeck, 2019; Ateh, 2015). Consequently, limited interpretation of evidence can prevent teachers' instructional decision-making, particularly about designing the appropriate next steps and providing feedback that moves learning forward (Ropohl & Rönnebeck, 2019). Regarding teachers' actions after the interpretation of evidences, research shows that their decisions often do not meaningfully support the teaching and learning process. Many teachers face challenges in providing effective feedback. When feedback is given, it is often general, limited in depth, and non-individualized (Ropohl & Rönnebeck, 2019). Teachers also tend to focus mainly on whether students' answers are correct, rather than responding to students' thinking in ways that support deeper learning (Ateh, 2015). As a result, formative assessment cycles often remain incomplete and, consequently, may not effectively promote students' learning (Cisterna & Gotwals, 2018).

Overall, both pre- and in-service teachers need further support in order to use formative assessment for the development of competencies. At the same time, research on assessing CC competencies remains limited, particularly with respect to formative assessment in primary education (e.g., Cebrian et al., 2025). There is also a lack of guidance for teachers on how to use assessment tools effectively, which highlights the need for meaningful support (Redman et al., 2021).

Based on the above, the study aims to explore how pre-service teachers design and develop activities for assessing CC competencies. More specifically, emphasis is given to the phase of the planning of the formative assessment, which is considered as a critical component of its effectiveness (e.g., Grangeat et al., 2021). Accordingly, the main research question of the study is, "*How do pre-service teachers design assessment sequences to support the development of the CC competencies?*", which is analyzed through two sub-questions:

- What CC competency objectives do pre-service teachers set to assess in their activities?

- How do pre-service teachers structure the elements of formative assessment?

Methods

Empirical Study Description

This study involves nineteen pre-service primary teachers, who participated in a 13-week seminar course of the Department of Primary Education at the University of Crete, developing teaching scenarios about the development of CC competencies with the integration of assessment dimension. The empirical study is divided into two phases, as presented in Table 1.

Table 1. Description of CC competencies categories.

Empirical Study Phases	Meetings	Content
Phase A *Participants' Preparation*	***1st***	*CC scientific concepts*
	2nd - 3rd	*CC competencies*
	4th	• *Assessment of CC competencies* • *Formative assessment strategies*
	5th - 6th	• *Framework for the design of assessment tools and activities* • *Examples of assessment activities and tools*
Phase B *Design & Development of Teaching Scenarios*	***7th***	*Setting Learning Objectives for Whole Teaching and Individual Activities*
	Reflection & Personalized feedback (per group)	
	8th – 9th	• *Refinement of the Learning Objectives* • *Activities & Tools Design: Determining the indicators to monitor learner progress*
	Reflection & Personalized feedback (per group)	
	10th	*Activities & Tools Design: Determining the activity characteristics (e.g., task format)*
	Reflection & Personalized feedback (per group)	
	11th	*Development of activities and assessment tools (plus Worksheets)*
	Reflection & Personalized feedback (per group)	
	12th	*Teaching scenario refinement*

During **Phase A (**six meetings), participants were introduced to a. core concepts of CC (e.g., drivers, causes) and climate literacy, b. principles for assessing CC competencies, c. formative assessment strategies, and d. specific examples of designing and utilizing assessment tools and activities to foster CC competencies. Then, in **Phase B**, pre-service teachers developed teaching scenarios, emphasizing the integration of the assessment tools and activities to foster CC competencies. Six plenary meetings were thus dedicated to supporting participants during the development process. Additionally, four individual meetings were held with each group between

the main meetings to address challenges, provide personalized feedback, and support reflection on their teaching scenario.

Data Collection

Data were collected through participants' developed teaching scenarios (n=7), including the assessment activities and tools that they designed. Due to the nature of the research, qualitative methods of content analysis were used (Bryman, 2016). Specifically, the category systems were developed based on the relevant literature and were refined or adjusted in response to the empirical data.

Data Analysis

Data analysis examines participants' teaching scenarios along two main axes: a. CC competencies objectives, and b. elements of formative assessment. Regarding the first sub-research question, a categorization scheme for the CC competency objectives was developed based on literature (e.g., Taurinen et al., 2024; Bianchi et al., 2020; Wiek et al., 2011) and empirical data, as presented in Table 2.

Table 2. Description of objectives for CC competencies.

Categories	Criteria
Systems Thinking	• Complex systems' features (e.g. feedback loops) • Various domains (e.g. society, economy) • Effects of actions/choices
Futures Thinking	• Time scale o Real data (past-present) o Trends (future) • Future scenarios development
Strategic Competency	• Fostering action-taking • Design of solutions/action plans
Normative Competency	• Evaluation of the sustainability of current or future states • Sustainability values • Decision-making (e.g., addressing dilemmas
Interpersonal Competency	• Evaluation of diverse perspectives • Communication, negotiation, and collaboration skills

Additionally, each activity's objectives were examined to identify the specific dimensions of CC competencies—knowledge, skills, and attitudes. Specifically, ***knowledge*** **objectives** focus on understanding and elaborating principles, theories, and facts about scientific core concepts and phenomena of CC. ***Skills objectives*** emphasize applying knowledge and expertise to accomplish tasks, fostering cognitive and practical skill development. ***Attitude objectives*** involve forming personal values, attitudes, and intentions that influence individuals' behavior.

Regarding the second research sub-question, the assessment activities and tools included in the participants' teaching scenarios were analyzed to identify how formative assessment elements were structured and combined across the scenarios. For this purpose, a categorization scheme (see Table 3) was applied, which was based on formative assessment elements described in the

literature (e.g., Dini et al., 2020; Grob et al., 2019; Black & Wiliam, 2018) and refined through the empirical data.

Table 3. Description of Formative Assessment Elements.

Categories	Description
Using Assessment Criteria	Specific criteria are used to assess the students' performance
Eliciting Information	Activities designed to capture aspects of competencies – knowledge, skills, attitudes.
Interpreting Information	Interpreting the collected evidence to identify students' progress and needs in developing CC competencies.
Providing Feedback	Providing information/comments to support CC competencies development and enhance learning outcomes.
Applying Feedback	The instructional design supports the direct use of feedback in following tasks.

Findings

CC competencies objectives

To address the first research sub-question about the CC competency objectives that pre-service teachers set to assess in their activities, Tables 4-5 summarize the findings.

According to the analysis of the participants' teaching scenarios, Table 4 presents the absolute frequency of the CC competencies objectives that addressed in the assessment activities developed by the pre-service teachers. Most learning objectives focus on Systems Thinking (n=30), while the other competencies were covered less frequently, especially Interpersonal Competency. This indicates a priority given to assessment of Systems Thinking over the other competencies.

Table 4. Learning objectives for CC competencies.

Categories	Absolute Frequency
Systems Thinking	30
Futures Thinking	14
Strategic Competency	17
Normative Competency	17
Interpersonal Competency	10

Additionally, Table 5 presents the absolute frequency of the different dimensions of CC competencies, demonstrating the tendency of participants to primarily assess the cognitive dimension, while indicating an effort to include skills assessment (n=22). Assessing values seems challenging for participants, resulting in a considerably lower frequency of values-related objectives (n=12) compared to the other two dimensions.

To answer the second research sub-question on how pre-service primary teachers structure formative assessment elements, Tables 6-7 and Figure 1 were created to summarize the findings.

Table 5. Dimensions of CC Competency Objectives.

Categories	Frequency
Knowledge	27
Skills	22
Attitudes	12

Formative Assessment Elements

Specifically, Table 6 presents how many times participants designed each of formative assessment elements. Participants used only assessment criteria that they designed themselves without considering engaging students in this process. These criteria were typically presented as checklists or detailed rubrics. Regarding "eliciting information", participants recognized its importance and designed different types of elicitation tasks beyond whole-class discussion or simple questioning, including tasks requiring the creation of artifacts (e.g., concept maps, leaflets, posters) and demonstration of skills (e.g., diagram construction, action-plan design). In addition, participants most of the times did not plan just to collect data, but also to make sense of it, identifying points in their scenarios where interpretation would occur, based either on predetermined criteria or on more intuitive judgement. They also specified if evidence would be interpreted by the teacher or by students through self-assessment and peer-assessment. However, although the element "interpreting information" was frequently mentioned, feedback based on these interpretations was planned to be given much less often, indicating a difficulty for pre-service primary teachers. They organised the provision of feedback through multimedia (e.g., video, images), rubrics and individual or plenary discussions. Finally, "applying feedback" was the least frequently designed element by participants, indicating that feedback rarely leads to follow-up actions. In the few cases that participants integrated this element in their teaching scenarios, they focused on creating opportunities for students to revise their answer, artifact or their performance on the task.

Table 6. Elements of Formative Assessment.

Categories	Frequency
Using Assessment Criteria	16
Eliciting Information	51
Interpreting Information	47
Providing Feedback	27
Applying Feedback	6

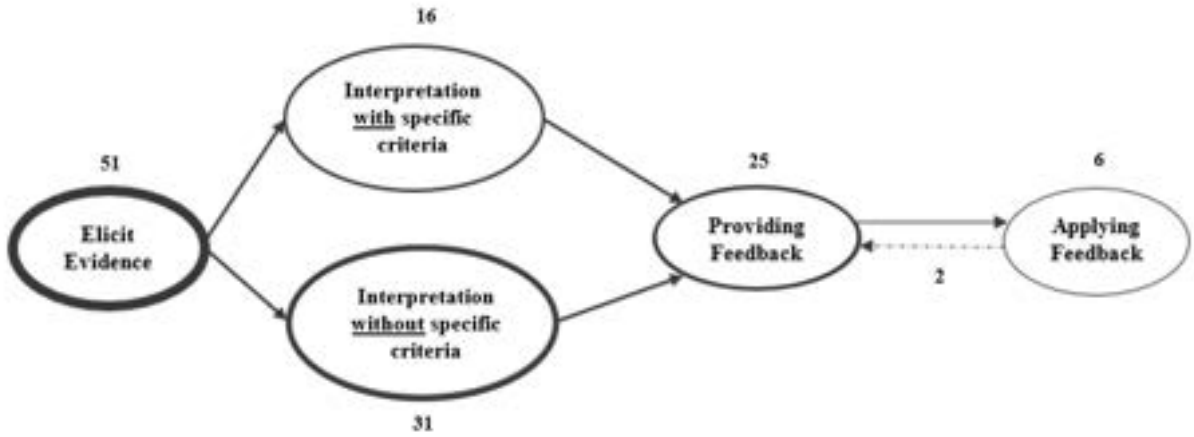
Table 7 provides a more detailed view by breaking down participants' choices of formative assessment elements by CC competency. While the previous table summarized the elements used in general, Table 7 shows the pattern of element selection within each competency. Reading across the rows, the table indicates that complete formative assessment cycles were only attempted for Systems Thinking and Futures Thinking. The findings also reveal that pre-service teachers may consider Systems Thinking a demanding competency for both themselves and their students and they tried to better support its development. Accordingly, most formative assessment elements appear more frequently in Systems Thinking, particularly "Providing Feedback".

Table 7. Formative Assessment Elements across CC Competencies.

FA Elements / CC Competencies	Using Assessment Criteria	Eliciting Information	Interpreting Information	Providing Feedback	Applying Feedback
Systems Thinking	8	18	17	14	4
Futures Thinking	2	7	7	3	2
Strategic Competency	3	10	9	3	0
Normative Competency	1	10	8	5	0
Interpersonal Competency	2	6	6	2	0

Furthermore, the analysis of teaching scenarios revealed that participants structured the formative assessment elements that were examined earlier (see Table 6 & 7), forming integrated assessment pathways within activities. These pathways were illustrated for each CC competency, with Figure 1 presenting a comprehensive pathway summarizing all CC competencies, where line thickness reflects the frequency of each strategy and the dashed line indicates a return to a previous phase. However, providing feedback is challenging for pre-service teachers, who do not often incorporate it into their activities. When included, it is typically given at the end and does not provide students with the opportunity to apply it constructively.

Figure 1. Comprehensive assessment pathway of all CC competencies.



Discussion & Conclusions

The findings show how pre-service teachers planned formative assessment elements within teaching scenarios developed to support the development of CC competencies. Overall, they primarily targeted knowledge-related objectives, with a particular emphasis on Systems Thinking. The findings also reveal challenges in relation to feedback practices.

More specifically, pre-service teachers designed activities aimed at fostering climate literacy, with a particular emphasis on assessing the cognitive dimension of CC competencies (Redman et

al., 2021), while also making efforts to address the skills dimension. This pattern may reflect greater confidence in assessing knowledge-related objectives. The participants' choices are consistent with the literature, which shows that competencies related to values, attitudes, and action appear to be addressed to a more limited extent (Monroe et al., 2019). Additionally, pre-service teachers placed particular emphasis on Systems Thinking in their assessment activities, recognizing it as a key CC competency and essential for CC teaching, in line with what is highlighted in the literature (Lorenzo-Rial et al., 2025; Levrini et al., 2019).

Moreover, the findings provide insights into how formative assessment elements were structured by pre-service teachers and how they were integrated into teaching scenarios. Participants placed emphasis on observing the overall learning process and planned to use, apart from common activities such as discussions and reports, a range of activities to elicit different types of information (e.g., written, oral, observational) about students' progress in CC competencies. This emphasis on "Eliciting Information" is in line with the literature, which highlights its importance for effective formative assessment (e.g., Dini et al., 2020; Ateh, 2015). In addition, feedback is either underutilized or avoided by pre-service teachers, highlighting a weakness in the integration of this element to their teaching (Ropohl & Rönnebeck, 2019). The lack of planning for providing and using feedback may have led to fewer planned formative assessment cycles and less support for learning goals, such as competency development (Cisterna et al., 2018). Therefore, pre-service teachers may benefit from support in feedback practices, as a core element of assessment to promote the development of competencies (Grangeat et al., 2021), and more specifically to foster climate literacy.

To conclude, this study highlights how pre-service teachers approach formative assessment for CC competencies at the planning level. The findings indicate that pre-service teachers place emphasis on addressing knowledge-oriented objectives and eliciting evidence of students' learning more systematically, while they struggle to plan systematic feedback and opportunities to act on it. Teacher education could equip pre-service teachers with the knowledge and skills needed to use contemporary assessment approaches, such as formative assessment.

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Part 15 / Strand 15

Pre-Service Science Teacher Education

Co-editors: *María Martínez Chico & Carla Morais*

Part 15 / Strand 15 Pre-Service Science Teacher Education

Professional knowledge of pre-service science teachers, pre-service teacher preparation, instructional methods in pre-service teacher education, programmes and policy, field experience, relation of theory with practice, and issues related to pre-service teacher education reform.

Sub-themes:

1. Pedagogical Approaches in Pre-service Science Teacher Training
2. Linking Theory and Practice in Pre-service Teacher Education
3. Field Experiences and Practicums in Science Teacher Education
4. Reform and Innovation in Pre-service Science Teacher Programs

Contents

Strand 15: Pre-Service Science Teacher Education 1296

Content Knowledge And Its Impact On Pedagogical Content Knowledge: A Case Study Of A Pre-Service Chemistry Teacher In A Residency Program 1298

What Do Pre-Service Early Childhood Teachers Learn About The Nature Of Models When Engaging In Model-Based Inquiry? 1307

Prospective Physics Teachers' Perceptions Of An Objective Structured Teaching Examination (OSTE) 1316

Dealing With Students' Misconceptions In A Virtual Reality Classroom In Pre-Service Teacher Training 1325

Primary Pre-Service Teachers' Professional Identity Development For Teaching Climate Change 1330

Exploring Pre-Service Primary Teachers' Pedagogical Content Knowledge Of Interdisciplinarity In Science And Mathematics 1340

Linking Pre-Lesson Content Representations And Post-Lesson Reflections: AI-Based Insights Into Context-Specific PCK Development 1348

Technology And Pedagogy In Science Teacher Education: Promoting Teacher Candidates' Skills In Instructional Design And Learning Management Systems 1357

Science Teacher Educators: Career Narratives And Life Histories 1363

Examining Pre-Service Chemistry Teachers' Perceptions About Their Interactions With Mentors And Peers During The COVID-19 Pandemic 1371

Physics as Culture: Dialogues for a Critical and Sustainable Teacher Education 1380

Beyond Human Mentors – Exploring AI-Driven Reflection In Teacher Training 1386

Analysis Of Physics And Chemistry Pre-Service Teachers' Perceptions About Their Teaching Identity And Professional Development 1396

Pre-Service Physics Teachers' Conceptions About What It Means To Understand Physics: A Phenomenographic Study 1404

Fostering An Understanding Of The Significance Of Insect Care In Pre-Service Teacher Training 1410

Exploring The Attention Dimension Of Plant Awareness Through Drawing: From Stereotypes To Detailed Observations 1419

Agile In Academia: Assessing Scrum's Potential For University Teaching 1425

ESERA 2025 Copenhagen

Strand 15: Pre-Service Science Teacher Education

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Introduction

Pre-service science teacher education plays a central role in preparing future teachers for the demands of science teaching. Beyond disciplinary knowledge, teacher education programmes are expected to promote the development of Pedagogical Content Knowledge (PCK in advance), reflective and inquiry-oriented teaching practices, professional identity and the capacity to respond to emerging educational and societal challenges. Research in this field has therefore focused on how future teachers connect theoretical knowledge with teaching practice while developing the competences required for their profession.

The contributions in this chapter reflect several current directions in pre-service science teacher education across different educational contexts and science disciplines. A central aspect addressed is the development of professional knowledge and competence, including PCK, pedagogical reasoning, topic-specific understandings of science teaching and learning, and the integration of disciplinary, pedagogical and technological knowledge. Across the chapter, these issues are considered and examined in relation to different areas of Science Education, emphazising the importance of understanding how future teachers construct the knowledge needed to design, implement and reflect on science teaching-learning.

A common feature across many contributions is the exploration of innovative approaches to teacher education. Several contributions examine how pre-service teachers learn through mentoring, guided reflection, collaborative work, practicum experiences and other forms of approximation to practice. The chapter reflects a broad view of teacher education in which learning to teach is not reduced to the acquisition of conceptual knowledge, but is also understood as participation in professional communities, identity development, and engagement with the practical, ethical and relational dimensions of teaching. The chapter also includes works that extends this perspective to science teacher educators themselves, thereby drawing attention to teacher education as a professional field in its own right.

Another trend across the different studies included in the chapter is the prominent of innovation in teacher education design. This can be noticed in some contributions that examine digital and technology-supported learning environments, including online learning, AI supported reflection, and digital tools for supporting professional learning and reflective practice. Other studies focus on innovative teaching approaches and organizational formats to support professional learning through a deeper understanding of the nature of scientific models after implementing approaches such as Model-Based Inquiry (MBI).

The chapter also reflects growing attention to broader societal challenges that increasingly shape science teacher education. Sustainability, climate change education, environmental awareness and socially relevant perspectives on science illustrate the role of pre-service teacher education in preparing future teachers to engage learners with contemporary scientific and societal issues.

Methodologically, the contributions illustrate the diversity of research approaches currently used in science teacher education, including qualitative interview studies, implementation and design-based research, questionnaire-based studies, case studies, phenomenographic approaches and

mixed-methods designs. This wide range of methodological approaches reflects the breadth and diversity in the field, including issues of teacher knowledge, identity, reflection, mentoring, innovation, and curricular challenges. Furthermore, all the contributions position initial science teacher training as a dynamic area of educational research, constantly evolving and focused on how to promote the learning of future teachers for the effective and ambitious teaching of science in current contexts marked by the complexity of the content, the often negative perception of science, digital transformation, and pressing social challenges.

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Content Knowledge And Its Impact On Pedagogical Content Knowledge: A Case Study Of A Pre-Service Chemistry Teacher In A Residency Program

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This study explores how variations in content knowledge (CK) are reflected in the integration of pedagogical content knowledge (PCK) in the student teaching of a pre-service chemistry teacher, Marie, participating in a Pedagogical Residency Program (PRP) in Brazil. The PRP is an 18-month teacher education initiative designed to immerse pre-service teachers in school contexts during the final stages of their undergraduate programs, fostering reflection on teaching practice under the guidance of experienced teachers and university supervisors. Data were collected through lesson plans, reports, audiovisual recordings of classroom practice, and interviews using the stimulated recall technique. The analysis was guided by the PCK framework proposed by Park and Oliver, with particular attention to the integration of PCK components. The findings indicate that patterns of PCK component integration varied across teaching topics and were sensitive to the nature of the content. In topics more closely aligned with Marie's disciplinary background, such as the history of chemistry, PCK components were more extensively articulated. In contrast, lessons involving DNA structure and chemistry-art connections revealed more fragmented integration, suggesting that limitations or uncertainties in CK may constrain the coordination of PCK components in situated teaching contexts. These findings highlight the role of CK in shaping PCK and contribute to current discussions on the enacted and topic-specific nature of teachers' professional knowledge in initial teacher education.

Keywords: Pre-service teacher education, Professional development, Educational Policy

Introduction

In Brazil, recent public policies have been seeking to address longstanding challenges in teacher education, such as low professional valorization and the need to better integrate theory and practice during pre-service training. Within this scenario, the Pedagogical Residency Program (PRP) was created as a national policy designed to immerse pre-service teachers in school contexts during the final stages of their undergraduate programs, fostering reflection on teaching practice under the guidance of both school-based mentors and university supervisors.

To understand how such practice-based programs contribute to teacher professional learning, it is necessary to consider the specific types of knowledge involved in teaching. A key construct for understanding teacher professional knowledge in such contexts is the Pedagogical Content Knowledge (PCK). PCK, a concept introduced by Shulman (1986), refers to the unique knowledge teachers possess about how to teach a particular subject, distinguishing teaching expertise from disciplinary expertise. Since its introduction, PCK has been widely recognized as a central element of teaching, as it enables teachers to transform subject matter knowledge into forms that are pedagogically meaningful to learners.

Although the literature has consistently highlighted the importance of content knowledge (CK) for teaching (Magnusson et al., 1999; Neumann, Kind, & Harms, 2019), the relationship between CK and PCK remains theoretically and empirically complex. In this study, CK is not conceptualized as a component of PCK, but rather as a condition of possibility that shapes how PCK components are mobilized and integrated during teaching practice. Previous studies suggest

that insufficient CK may constrain teachers' instructional decisions, limit their responsiveness to students' ideas, and reduce the coherence of their pedagogical approaches (Gess-Newsome & Lederman, 2019). However, much of this research has focused on identifying correlations between CK and PCK or documenting their parallel development, rather than examining how variations in CK shape the integration of PCK components in situated teaching contexts.

In response to this gap, this study examines variations in CK in chemistry and their relationship with the integration of PCK components in the teaching practice of a pre-service chemistry teacher participating in the PRP. By focusing on different science topics, the study explores patterns of integrations of PCK components during instructional planning and classroom enactment. Guided by this perspective, the study addresses the following research question: How do changes in a pre-service chemistry teacher's content knowledge influence the integration of PCK components across different teaching topics within the PRP?

Framing

Pedagogical Content Knowledge

Teachers develop a unique body of professional knowledge throughout their education and teaching experiences, which distinguishes teaching from other professions. This knowledge encompasses not only subject matter knowledge, but also an understanding of how specific content can be taught and learned in particular contexts. Grossman (1990) conceptualizes this body of knowledge as the knowledge base for teaching, highlighting that effective teaching relies on the integration of multiple forms of knowledge developed through formal education and classroom practice.

Within this knowledge base, Pedagogical Content Knowledge (PCK) occupies a central position. Introduced by Shulman (1986), PCK refers to the distinctive knowledge teachers use to transform subject matter into pedagogically meaningful representations for learners. It is this form of knowledge that differentiates teachers from disciplinary specialists, as it encompasses not only what is taught, but how and why specific instructional approaches are used to promote student understanding.

Since its original formulation, the concept of PCK has been refined and expanded in the literature, while remaining a key construct for understanding teaching practice. Among the various models proposed, the pentagonal model developed by Park and Oliver (2008) has been particularly influential in science education research. This model conceptualizes PCK as comprising five interrelated components: Orientations to Teaching Science (OTS), Knowledge of Assessment of Science Learning (KAS), Knowledge of Instructional Strategies for Teaching Science (KIS), Knowledge of Science Curriculum (KSC), and Knowledge of Students' Understanding in Science (KSU). According to Park and Oliver (2008), effective teaching requires not the isolated use of these components, but their dynamic and coherent integration during instructional practice.

An important assumption of the pentagonal model is that improvements in one PCK component should be accompanied by corresponding growth in the others. From this perspective, PCK is not a static body of knowledge, but a dynamic construct that is enacted and reshaped through teaching, reflection, and interaction with students. Teaching, therefore, is understood as an adaptive process in which teachers continuously interpret classroom situations, make instructional decisions, and revise their approaches in response to students' understanding.

While PCK has been widely studied as a form of professional knowledge, its relationship with content knowledge (CK) remains theoretically and empirically complex. Studies have emphasized that a certain level of CK is necessary for effective teaching and for the development

of PCK (Magnusson et al., 1999; Neumann, Kind, & Harms, 2019). Weak content knowledge may constrain teachers' instructional decisions, limit their ability to anticipate student difficulties, and reduce the coherence of their pedagogical strategies (Gess-Newsome & Lederman, 1995). However, much of the existing research has examined CK and PCK either as parallel domains or through correlational approaches, offering limited insight into how CK shapes the organization of PCK during teaching practice.

In this study, CK is not conceptualized as a component of PCK. Rather, CK is understood as a condition of possibility that enables the integration of PCK components in specific instructional contexts. From this perspective, variations in content mastery may influence how teachers mobilize instructional strategies, interpret students' ideas, align their teaching with curricular goals, and design assessment practices. When CK is robust, teachers may be better positioned to integrate multiple PCK components coherently; when it is limited or challenged, such integration may become fragmented or uneven.

Building on classical conceptualizations of PCK (Shulman, 1986; Grossman, 1990; Park & Oliver, 2008), this study addresses an analytical question by focusing on the integration of PCK components rather than on their isolated presence or development. By examining how variations in CK across different teaching topics shape the integrations of PCK components in a pre-service chemistry teacher, the study contributes to ongoing discussions about the role of CK in teacher education and the conditions under which PCK can be effectively enacted during initial teacher preparation.

Methodology

Context And Participants

Data were collected within the Brazilian Pedagogical Residency Program (PRP). The PRP is an 18-month program in which undergraduate students engage in sustained school-based experiences under the supervision of experienced school teachers and a university educator. Participants receive government-funded scholarships and take part in regular planning meetings, classroom observations, and teaching activities.

The study involved six undergraduate chemistry students enrolled in the PRP. From this group, one participant, here referred to as Marie, was selected for in-depth analysis. This purposeful case selection was guided by the analytical goals of the study rather than by representativeness. Marie participated in all phases of the program and planned and implemented three distinct teaching lessons addressing different content domains: Solo Role Play Game (RPG) (history of chemistry), The chemical structure of DNA, and Chemistry and Art: A Playful Exploration of Organic Functions. These science topics differed in terms of disciplinary focus and content complexity, making the case particularly suitable for examining how variations in content knowledge shape the integration of pedagogical content knowledge components.

At the time of data collection, Marie had completed most of her K-12 education in private institutions and was pursuing a teaching degree alongside her chemistry studies. She was also enrolled in a master's degree program in science education, with a particular interest in the history of science. This background provided a rich context for examining how content knowledge developed unevenly across topics and how such variations were reflected in her pedagogical reasoning and instructional decisions.

Data Collection

Multiple data sources were used to capture both planned and enacted aspects of Marie's teaching. These included written reports, lesson plans, audiovisual recordings of weekly PRP meetings,

and recordings of the three lessons taught at the school she was doing her student teaching. These materials provided access to Marie's instructional decisions, reflections, and interactions with students and peers throughout the teaching process.

In addition, a semi-structured interview using the stimulated recall technique was conducted to support reflective analysis of her teaching practices. During the interview, selected excerpts from lesson recordings and planning materials were used to prompt Marie to reflect on her instructional choices, content-related decisions, and perceptions of student understanding (Nilsson, 2014). This approach allowed for deeper insight into the relationship between content knowledge and pedagogical reasoning as articulated by the participant herself.

Data Analysis

Data analysis followed a qualitative interpretative approach consistent with the study's analytical focus on the integration of PCK components. Initially, a thematic analysis was conducted following the procedures outlined by Clarke and Braun (2017). Inductive coding was used to identify salient themes emerging from the data, capturing patterns related to instructional strategies, student understanding, assessment practices, and content-related reasoning.

Subsequently, a deductive analytical phase was conducted in which the codes were organized according to the five components of PCK proposed by Park and Oliver (2008): Orientations to Teaching Science (OTS), Knowledge of Assessment of Science Learning (KAS), Knowledge of Instructional Strategies (KIS), Knowledge of Science Curriculum (KSC), and Knowledge of Students' Understanding in Science (KSU). This process enabled the identification of how each component was mobilized across different teaching topics.

To examine the integration of PCK components, PCK maps were constructed following the methodology proposed by Park and Chen (2012). These maps represent the frequency and intensity of connections between PCK components within each teaching sequence, allowing for comparative analysis across topics. Following this approach, all identified connections between components were initially treated as having equal strength, and interactions involving more than two components were represented through pairwise connections (Park & Chen, 2012). Episode-level maps were then aggregated to produce a single map for each teaching sequence, reflecting overall patterns of PCK integration (Park & Suh, 2019). Variations in the frequency of connections were interpreted as differences in the strength of relationships between components and were visually represented by the thickness of the connecting lines in the maps.

Findings and Results

Marie's Content Knowledge

Instead of providing an exhaustive assessment of Marie's CK, we focused on how her understanding is enacted during her teaching across the three lessons developed within the PRP. This section examines how Marie mobilizes chemical concepts in interaction with students, how she connects ideas across topics, and how moments of confidence and uncertainty emerge in situated instructional contexts.

Across the three teaching sequences, Marie generally draws on chemistry concepts to support explanations and to connect chemistry with historical, biological, and everyday contexts. In the Solo Role Play Game (RPG) lesson, her enactment of CK is marked by the sustained use of historical narratives and conceptual reasoning to frame the development of key chemical ideas. While discussing the theory of phlogiston and Lavoisier's experiments, Marie consistently situates chemical concepts within their historical context, emphasizing the tentative and human character of scientific knowledge. For instance, when explaining the increase in mass observed

during the combustion of iron, she highlights the role of oxygen incorporation, explicitly connecting the experimental observation to the law of conservation of mass*:* "When we burn steel wool, the oxygen from the air is incorporated, and that is why the mass increases" (Marie, RPG lesson). Throughout this lesson, Marie mobilizes CK to respond to students' questions, clarify misconceptions, and sustain the narrative logic of the activity.

In the lesson on the chemical structure of DNA, Marie's enactment of CK reveals both coherent explanations and localized conceptual difficulties. She draws extensively on prior chemistry content, particularly organic chemistry and intermolecular interactions, to support students' understanding of DNA structure. When discussing base pairing, she accurately explains the difference in the number of hydrogen bonds between base pairs: "Guanine with cytosine makes three intermolecular interactions, whereas adenine with thymine makes two" (Marie, DNA Structure lesson). She also makes deliberate connections between the numbering of carbon atoms in organic molecules and the 5′–3′ orientation of the DNA strand, explicitly linking prior chemistry concepts to a biological structure.

At the same time, a conceptual inaccuracy emerges when Marie characterizes RNA as simply "one half" of the DNA molecule, suggesting that the distinction lies primarily in the number of strands rather than in structural differences in the sugar component. This moment illustrates how CK is not uniformly enacted across all aspects of the topic, even within an otherwise coherent explanation. Importantly, this struggle does not interrupt the overall flow of the lesson, but it indicates a point where limitations in CK may shape the way specific ideas are represented to students.

In the Chemistry and Art lesson, Marie mobilizes CK to support interdisciplinary connections between chemistry, artistic practices, and everyday materials. She explains the chemical composition of paints, solvents, binders, and pigments, frequently translating abstract representations into more accessible forms. While discussing the limonene molecule, she explicitly addresses structural representations, noting that "each vertex represents a carbon atom" (Marie, Chemistry and Art lesson). She also draws on organic chemistry concepts to differentiate between functional groups, such as alcohols, aldehydes, carboxylic acids, and ketones, often using the board to support visual explanation.

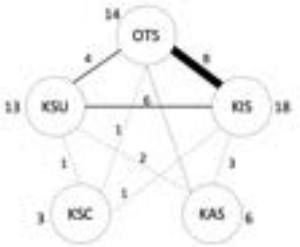
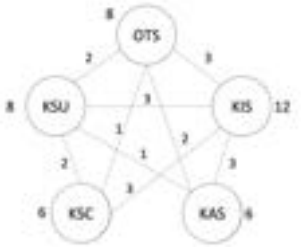
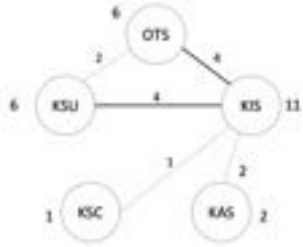
Across these lessons, Marie's CK is enacted in ways that are closely intertwined with instructional goals, student participation, and the unfolding of classroom interactions. Rather than appearing as a fixed background resource, CK emerges as a situated and dynamic element of teaching, occasionally revealing tensions or gaps that become analytically relevant when examined in relation to the integration of PCK components.

Marie's Integration of PCK Components Across Topics

Marie's PCK maps illustrate how different components of PCK were articulated across the three teaching topics developed within the PRP. Table 1 shows the PCK maps for three topics, highlighting the frequency and intensity of component connections. Rather than indicating levels of proficiency, the maps make visible patterns of integration among PCK components, allowing for a comparative analysis of how these configurations vary according to content and instructional context.

Across all three topics, KIS occupied a central position in Marie's PCK maps, functioning as a hub through which other components were connected. This prominence suggests that instructional decision-making played a key role in structuring her teaching practice, regardless of topic. However, the overall degree and configuration of integration differed across the three lessons.

Table 1. PCK Map for the Resident Marie.

Solo RPG (Role Play Game)	The chemical structure of DNA	Chemistry and Art: A Playful Exploration of Organic Functions
		
1-3: ----------	4-7: ———	>8: ■■■

OTS: Orientations of Teaching Science; KIS: Knowledge of Instructional Strategies; KAS: Knowledge of Assessment of Science Learning; KSC: Knowledge of Science Curriculum; KSU: Knowledge of Students´ Understanding in Science.

The Solo RPG lesson exhibited the highest number of connections among PCK components, indicating a more articulated integration pattern. In this topic, Marie frequently connected KIS with KSU, OTS, and, to a lesser extent, KSC. Her choice of an RPG-based strategy to address the History of Chemistry illustrates how instructional decisions were informed by epistemological and pedagogical concerns. As she explained in the interview, "I wanted a different way to approach the History of Chemistry, which is rarely addressed by teachers, partly because it is challenging and often reduced to names and dates that reinforce a heroic view of science" (Marie, interview). This strategy created opportunities for student participation and critical engagement, supporting the articulation between KIS and KSU observed in the maps.

The integration between KIS and KSU emerged as a recurrent pattern across all topics. Marie frequently used questions and dialogic interactions to elicit students' prior ideas and adjust her explanations accordingly. For example, in the DNA lesson, she asked: "What do you think of when you hear DNA?" (Marie, DNA class), signaling an attempt to anchor instruction in students' existing conceptions. These interactions contributed to the repeated coupling of instructional strategies with KSU, suggesting a student-oriented approach to teaching.

In contrast, KSC appeared less frequently integrated with other components, particularly in the Chemistry and Art lesson. Although Marie knew about the school's curriculum, such as prior content coverage, references to curriculum mainly informed localized instructional decisions rather than broader planning or assessment considerations. This pattern is consistent with previous studies that report weaker integration of KSC in PCK maps (Park & Chen, 2012). For instance, when planning the Chemistry and Art lesson, Marie noted that students had already studied organic functions and therefore intended to revisit alcohols and ketones based on students' observations of molecular structures: "To ask the students what they see as different and notable in this structure. If they mention the heteroatoms as expected, revisit the two organic functions present alcohol and ketone" (Marie, lesson plan). While this indicates curricular awareness, it was not systematically connected to assessment or to explicit curricular goals within the lesson.

The Chemistry and Art lesson displayed a more limited integration among PCK components overall. Although OTS, KIS, and KSU remained central, fewer connections involved KSC and KAS. Much of the interaction focused on identifying and revisiting previously taught concepts, as illustrated by questions such as "Do you remember the lesson on alcoholism? What

characterized alcohol?" (Marie, Chemistry and Art lesson). These patterns suggest that, in interdisciplinary contexts, Marie's PCK integration was primarily oriented toward activating and diagnosing prior knowledge rather than coordinating multiple components around shared curricular or assessment goals.

In the DNA structure lesson, Marie mobilized several PCK components, but the resulting integration was less articulated than in the RPG lesson. While KIS and KSU were frequently connected, links involving assessment and curriculum were sparse. The use of visual representations, such as images of the DNA double helix and X-ray diffraction photographs, supported the contextualization of abstract concepts, but these strategies were not consistently connected to assessment practices or curricular choices.

Discussion

The variability observed across Marie's PCK maps highlights the topic-specific and situated nature of PCK integration. Rather than reflecting stable characteristics of the teacher, these configurations appear to be shaped by the nature of the content, the degree of interdisciplinarity involved, and the extent to which CK could be mobilized to support instructional coherence. In topics more closely aligned with Marie's disciplinary background, such as the history of chemistry addressed in the RPG lesson, PCK components were more extensively articulated. In contrast, in topics requiring the integration of chemistry with biology or art, component integration was more fragmented, suggesting that limitations or uncertainties in content knowledge may have constrained the coordination of instructional, curricular, and assessment-related decisions.

The findings of this study contribute to ongoing discussions in PCK research by shifting the analytical focus from the identification of individual components to the examination of their integration in situated teaching contexts. Recent studies have increasingly emphasized PCK as an enacted, dynamic, and topic-specific form of professional knowledge that emerges through instructional decision-making rather than as a stable body of knowledge possessed by teachers (Carlson et al., 2019; Kind & Chan, 2019). In line with this perspective, the variation observed across Marie's PCK maps reinforces the view that PCK integration is sensitive to content characteristics and instructional demands.

While prior research has consistently documented relationships between CK and PCK, often emphasizing their co-development or mutual dependence, the present study advances this discussion by examining how variations in content knowledge are reflected in the integration of PCK components within the teaching practice. Rather than treating PCK as a collection of discrete components or as a stable attribute of the teacher, this analysis explores the configuration and connections between components as they are enacted across different topics.

The comparative analysis of PCK maps across three teaching lessons demonstrates that integration patterns are not uniform, even within the practice of a single pre-service teacher. These variations cannot be fully explained by general teaching competence, but appear to be shaped by topic-specific demands, degrees of interdisciplinarity, and the extent to which CK can be mobilized to support instructional coherence. In this sense, the study moves beyond confirming that CK matters for PCK development, offering instead a fine-grained account of how CK influences the internal organization of PCK during instructional enactment.

Although based on a single case, the study does not seek to generalize about levels of PCK or teaching effectiveness. Instead, its contribution lies in illustrating the analytical potential of PCK maps for examining the situated and topic-dependent integration of pedagogical knowledge in initial teacher education. In doing so, the study opens possibilities for future research that explores

how different configurations of CK and instructional context shape the enactment of PCK across subjects, topics, and stages of teacher development.

Conclusion

This study examined how variations in CK are reflected in the integration of PCK components in the teaching practice of a pre-service chemistry teacher participating in a Pedagogical Residency Program. Rather than aiming to assess levels of CK or pedagogical expertise, the analysis focused on how content understanding was enacted and mobilized across different teaching topics.

The findings indicate that patterns of PCK integration varied across instructional contexts, suggesting that CK may condition how coherently PCK components are articulated during teaching. In topics more closely aligned with the teacher's disciplinary background, such as the history of chemistry addressed in the RPG lesson, PCK components were more extensively integrated. In contrast, in topics involving interdisciplinary demands, such as DNA structure and chemistry and art, the integration of components was more fragmented, highlighting how uncertainties or limitations in CK may constrain the coordination of instructional, curricular, and assessment-related decisions.

Although based on a single case, the findings underscore the importance of examining the enacted integration of knowledge components in practice-based programs such as the Pedagogical Residency Program. Future research could build on this approach by exploring how different configurations of content knowledge, instructional context, and support structures shape the development and enactment of PCK across subjects and stages of teacher education.

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What Do Pre-Service Early Childhood Teachers Learn About The Nature Of Models When Engaging In Model-Based Inquiry?

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This study investigates whether pre-service Early Childhood Education teachers at the University of Cádiz (Spain) develop a deeper understanding of the nature of scientific models after implementing a Model-Based Inquiry (MBI) Teaching-Learning Sequence (TLS). The TLS focused on the water cycle, using the ecological garden as a real-world learning context. Students' knowledge of model nature was measured before and after the TLS using the Spanish CoNaMo questionnaire. Statistical analyses revealed significant gains, particularly in the dimensions "beyond exact replicas" and "changing nature of models." These findings highlight the importance of designing TLS that foster authentic epistemic practices and explicitly address students' understanding of model nature to support the development of Pedagogical Content Knowledge (PCK) related to modelling and inquiry.

Keywords: Inquiry-Based Learning, Nature of Science, Pre-service Teacher Education

Introduction

Teaching science involves the challenge of engaging students in scientific practices such as modelling and inquiry. These practices not only support the understanding of complex concepts but also promote a deeper comprehension of the Nature of Science (NOS). However, implementing them effectively in classrooms requires teachers to have a strong Pedagogical Content Knowledge (PCK). Understanding the nature, purpose, and limitations of scientific models is essential in teacher education, as it shapes how future teachers approach science instruction and influences students' learning (Akerson et al., 2010). Science as a cultural product, through its explanatory models, theories, and concepts, has a substantial impact on citizens' lives (Tamayo et al., 2005). Consequently, instructional design should foster a more critical engagement with scientific knowledge.

Addressing NOS in science classes enables students to develop broader perspectives on science, which can in turn influence their own views of the world. According to Lenderman et al. (2023), explicit and reflective instruction, together with teaching approaches such as inquiry, appears to significantly enhance learners' understanding of NOS as a key component for authentic scientific literacy (Vázquez et al., 2001). Within NOS, the nature of models is particularly relevant (Brandão et al., 2011), including, for example, what students understand a model to be and how they consider the evolving nature of scientific models (Treagust et al., 2002).

Integrating these ideas in pre-service teacher education is essential, as it helps future teachers develop the metamodeling skills that form a core component of modelling competence (Nicolaou & Constantinou, 2014). It also provides them with the tools and resources needed to use scientific models appropriately and to recognise their role in scientific knowledge and in future science teaching (Oh & Oh, 2010). According to Bell and Clair (2015), young children can develop scientific skills and understanding aspects of science when guided by teachers with strong scientific preparation. This highlights the need to design instructional interventions that offer explicit and targeted support for learning about the nature of models.

Early Childhood Education is considered a critical stage for fostering the scientific thinking skills that underpin a more sophisticated understanding of the NOS (Bell & Clair, 2015). In this context, the main aim of this study is to analyse the progression in pre-service early childhood teachers' understanding of the nature of models through a training proposal that integrates inquiry and modelling to address the water cycle in a real context, namely the university ecological garden.

Theoretical Framework

PCK emerges from the interaction between disciplinary knowledge and the pedagogical strategies required to teach it. PCK enables pre-service teachers not only to understand the scientific concepts they teach but also to guide students in developing metacognitive and epistemological skills that support deeper engagement with scientific processes (Zohar & Barzilai, 2013). Beyond conceptual mastery, PCK incorporates the ontological status and epistemic value of scientific ideas, together with instructional strategies that promote reflection, scientific thinking, and cognitive self-regulation (Papadouris & Constantinou, 2017).

Epistemic practices are the core processes through which scientific knowledge is generated, validated, and communicated. They can be grouped into three interrelated spheres: empirical investigation, the development of explanations, and critical evaluation—corresponding to inquiry, modelling, and argumentation (Jiménez-Aleixandre & Crujeiras, 2017). Passmore and Svoboda (2012) emphasise that science instruction should engage students in constructing, using, evaluating, and revising models to explain, interpret, and predict phenomena, positioning modelling as a central feature of scientific knowledge (Nersessian, 2002). This work is closely tied to inquiry, which involves asking questions, collecting data, and identifying patterns to support models, and to argumentation, which enables students to justify explanations, assess evidence, and refine conclusions in critical and reflective ways.

Instruction grounded in authentic scientific practices—such as Model-Based Inquiry (MBI)—integrates these three epistemic practices and supports students' understanding of scientific processes and the development of metacognitive skills (Seraphin et al., 2012; National Research Council, 2012). However, engaging in isolated practices is not sufficient for developing the full set of abilities required to work with models critically and reflectively. For this reason, model-based learning is conceptualised in terms of modelling competence, which includes modelling practices—constructing, applying, and revising models—and the metaknowledge needed to reflect on models, their nature, and the processes involved in modelling (Oliva, 2019; Nicolaou & Constantinou, 2014).

Within this framework, metamodeling enables students to understand the nature, purpose, and limitations of scientific models, promoting critical reflection on their use in science and in teaching (Schwarz et al., 2009; Gobert et al., 2011). Knowledge of the nature of models can be organised around four key ideas:

- Models are not exact replicas of phenomena but partial representations of reality (Jansen et al., 2019; Krell & Krüger, 2017; Upmeier zu Belzen & Krüger, 2010).
- Models serve explanatory, interpretive, and predictive functions, helping to make sense of scientific phenomena (Jansen et al., 2019; Krell & Krüger, 2017).
- Multiple models can exist for the same phenomenon, reflecting the diversity of perspectives and approaches in science (Justi & Gilbert, 2002; Upmeier zu Belzen et al., 2019).
- Models are provisional and evolving, subject to revision or modification based on new evidence, alternative theories, or different purposes (Crawford & Cullin, 2004).

PCK, by integrating disciplinary knowledge with pedagogical strategies oriented to epistemic practices such as modelling and inquiry, not only guides the teaching of scientific concepts but also shapes how pre-service teachers foster students' understanding of the nature of models. This perspective underpins the implementation of specific educational interventions, such as MBI Teaching-Learning Sequences (TLSs), which allow researchers to assess how future teachers develop PCK applied to modelling and epistemic reflection.

This study is part of a broader research project evaluating a TLS designed for pre-service teacher education and focused on developing PCK related to modelling and inquiry. Specifically, it examines whether students in the Early Childhood Education degree progress in their understanding of the nature of models after implementing a TLS on the water cycle using the MBI approach. The study is guided by the following research questions:

RQ1. Do students show changes in their understanding of the nature of models after implementing an MBI sequence?

RQ2. Which aspects of the nature of models show these changes?

Methodology

Participants and Educational Context

The study involved 52 students (1 male, 51 female) enrolled in the course Didactics of the Natural Environment, third year of the Early Childhood Education degree at the University of Cádiz, Spain, during the 2024–2025 academic year. A TLS based on the MBI approach was designed and implemented (Gómiz-Aragón & Aragón, 2025), focused on the water cycle, consisting of six 90-minute sessions. The university ecological garden served as a real learning context.

The TLS was structured in five phases to promote the progression of students' initial models of the water cycle toward more complex representations. Table 1 summarises the phases, the main activities, and the aspects of students' understanding of the nature of models (CoNaMo[1] dimensions) addressed in each phase. The four dimensions are: D1 (models beyond exact replicas), D2 (model utility), D3 (multiple model representations), and D4 (evolving nature of models).

Instrument

Data were collected using the CoNaMo questionnaire (Oliva & Blanco-López, 2021), designed and validated to assess knowledge of the nature of scientific models. The questionnaire, originally in Spanish, includes 20 Likert-type items on a 5-point scale (1 = strongly disagree; 5 = strongly agree), distributed across four dimensions (D1–D4), each with 5 items. Scores for each dimension range from 0 to 20 points, and the total score ranges from 0 to 80, providing a quantitative measure of students' understanding of scientific models.

Before administration, the instructor explained the study purpose, and students provided informed consent. The questionnaire was administered in paper format as a pretest at the beginning of the TLS and as a posttest at the end.

[1] From the Spanish *Conocimiento de la Naturaleza de los Modelos*, or 'Knowledge of the Nature of Models'

Table 1. Phases and Activities of the MBI TLS.

Phase	Activities	Nature of models dimensions
1. Defining the TLS objective	A1: Exploration of initial water cycle models through drawings and CoNaMo pretest questionnaire	Identification of prior ideas about model nature, utility, diversity, and evolution (D1, D2, D3, D4)
	A2: Reflection on water, the natural environment, and water footprint	Model utility for understanding and acting on socio-environmental water issues (D2)
2. Initial conceptions	A3: Explicit expression of initial water cycle models	Contrast different representations of the same phenomenon (D3)
	A4: Expression of conceptions about the nature of models	Awareness of what a model is, its purposes, diversity, and evolution (D1, D2, D3, D4)
3. Modelling-based learning	A5: Use of thought experiments and drawings for water cycle modelling	Understanding the need for a model to explain the phenomenon, alternative representations, and reflection on model evolution (D2, D3, D4)
4. Model application through inquiry	A6: Introduction of the garden as a learning context	Model utility for interpreting a real phenomenon in the environment (D2)
	A7: Formulation of the main inquiry question	Definition of the model's purpose to guide the investigation (D2)
	A8: Identification of difficulties and formulation of sub-questions	Need for different models or representations to explain various aspects of the phenomenon (D3)
	A9: Formulation of hypotheses, experiment design and execution, data collection, analysis, and conclusions	Use the model to predict and explain; represent results through drawings or diagrams (D2, D3)
	A10: Answering the main inquiry question	Reflection on model simplification and its utility for addressing the inquiry (D1, D2)
5. Model reconstruction	A11: Final review of the water cycle model through drawings and CoNaMo posttest	Review of final understanding of model nature, utility, diversity, and evolution (D1, D2, D3, D4)
	A12: Group reflective report on the teaching-learning process	Integration of reflection on model function and the learning process (D1, D2, D3, D4)

Data Analysis

To evaluate changes in pre-service teachers' understanding of the nature of models before and after the TLS, a within-group quantitative analysis was conducted. First, the reliability of the data was assessed using ordinal Cronbach's alpha for each dimension and for the overall scale (Table 2).

Table 2. Ordinal Cronbach's alpha for CoNaMo dimensions

CoNaMo dimensions	Pretest	Posttest
D1: Beyond exact replicas	0.700	0.782
D2: Utility	0.543	0.720
D3: Multiplicity	0.765	0.817
D4: Evolving nature	0.877	0.841
Global scale	0.883	0.891

Ordinal Cronbach's alpha values indicate improved internal reliability after the intervention. Pretest reliability ranged from acceptable (0.543) to high (0.877). Post-test reliability increased across dimensions, particularly D2 and D3, with the global scale rising from 0.883 to 0.891, reflecting strengthened reliability and potential improvement in questionnaire comprehension after the TLS.

Next, Wilcoxon signed-rank tests were performed to analyse differences between pre- and post-test scores, and effect sizes were calculated to determine the magnitude of these changes. All analyses were conducted using Jamovi software (version 2.4).

Result

Descriptive analysis of CoNaMo scores (Table 3) showed differences between pre- and posttest. In the pretest, D1 (Beyond exact replicas) had the lowest mean score (M = 2.3), while D4 (Evolving nature) had the highest (M = 3.1). The overall mean score was 2.8. After the intervention, all dimensions improved, with the largest gains in D1 (M = 2.9) and D4 reaching the highest post-test score (M = 3.5). The overall mean increased to 3.2, suggesting enhanced understanding of the nature of models.

Table 3. Descriptive statistics and Wilcoxon signed-rank test results

CoNaMo Dimensions	Pretest M	Pretest DS	Postest M	Postest DS	W	p-value	Effect size (r)
D1: Beyond exact replicas	2.3	0.6	2.9	0.7	230.0	<0.001	0.639
D2: Utility	2.9	0.4	3.2	0.5	220.0	0.002	0.513
D3: Multiplicity	2.9	0.4	3.3	0.6	146.5	<0.001	0.676
D4: Evolving nature	3.1	0.5	3.5	0.5	135.0	<0.001	0.750
Global	2.8	0.3	3.2	0.4	64.0	<0.001	0.891

Inferential analysis using the Wilcoxon signed-rank test confirmed statistically significant improvements across all dimensions. The largest effects were observed in D4 ($r = 0.750$) and the overall score ($r = 0.891$). Other dimensions also showed moderate gains: D1 ($r = 0.639$), D2 ($r = 0.513$), and D3 ($r = 0.676$). These results indicate that the intervention contributed to enhancing pre-service teachers' understanding of the nature of scientific models.

Discussion and Conclusions

The instructional intervention, implemented using a MBI approach, had a positive impact on pre-service teachers' understanding of the nature of models, consistent with previous research indicating that improvements are not explained by mere repetition of the instrument (Oliva & Caballero, 2020). Improvements were observed across all dimensions, with the largest gain in D4 (Evolving nature of models), aligning with studies suggesting that this dimension is particularly accessible for students (Jiménez-Tenorio et al., 2016).

This outcome can be attributed to the TLS design, where several activities explicitly highlighted the need to adapt models in response to new evidence, fostering understanding of their provisional nature. According to Engelschalt et al. (2024), recognizing that scientific models are evolving is closely linked to modelling knowledge itself—that is, understanding that models are provisional and develop over time.

In Activity 4, CoNaMo results were shared with the class, using multiple examples to clarify each dimension. This activity promoted dialogic metamodeling, grounded in students' own perceptions. In turn, Activity 5, a thought experiment, introduced new concepts and ideas that helped students develop more complex mental models of the water cycle, represented through detailed drawings. This activity thus exemplified the evolving and provisional nature of models in explaining a natural phenomenon.

In contrast, dimensions such as Multiplicity (D3) and Utility (D2) showed more moderate gains. This may be because the TLS did not include activities specifically designed to compare models with different functions or justify the utility of each representation for explanatory purposes. Future interventions could strengthen these dimensions by incorporating tasks that require selecting models according to their purpose, assessing the adequacy of different representations, and constructing explanations based on multiple types of models.

Overall, the results highlight the importance of explicitly addressing metamodeling, the epistemology of models, and the NOS in teacher education. Research indicates that understanding these aspects rarely develops implicitly through modelling practices; it requires intentional instructional strategies that make their epistemic dimensions visible (Schwarz, 2002). Interventions such as the one described in this study, which include guided reflection, model comparison, analysis of limitations, and discussion of model use, promote more robust learning. This is particularly relevant in pre-service teacher education, where developing PCK involves not only the ability to model but also the capacity to foster metacognitive and epistemic discourse about scientific models in the classroom.

Limitations

This study presents several limitations that should be considered when interpreting the results.

First, the TLS was implemented in the only course in the curriculum specifically dedicated to science education (Didactics of the Natural Environment) and within a limited timeframe, which may have constrained work on certain dimensions of the nature of models. The lack of continuity across other courses in the degree limits the opportunity to consolidate and deepen these learning outcomes.

Second, the study relied exclusively on a quantitative instrument. Although previously validated, it was not triangulated with qualitative sources, which limits a deeper understanding of students' conceptions and prevents clear attribution of observed changes to specific TLS activities. Without additional qualitative evidence, it is not possible to identify precisely which activities had the greatest impact or why some dimensions showed more moderate progression. Nevertheless, the instructor implementing the TLS (second author) was able to identify some key activities that likely supported improvements in certain dimensions. Future studies will examine other student outputs to better determine which activities contribute to the development of a more sophisticated understanding of the nature of models.

Finally, although results indicate gains in overall understanding of the nature of models, it is not possible to determine whether these learnings transfer specifically to the scientific model addressed, in this case, the water cycle model. Evaluating this relationship would require qualitative techniques, such as interviews or analysis of student journals, to explore how students connect what they learned with their own modelling processes in concrete tasks.

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Prospective Physics Teachers' Perceptions Of An Objective Structured Teaching Examination (OSTE)

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Assessments or examination procedures should be adequately aligned with the intended learning objectives and planned learning activities, ensuring that the assessment or examination is a valid and reliable measure of the desired learning outcomes. However, academic teacher education programmes often use assessment formats that do not align well with teachers' actual professional practice. Performance-based assessments provide an alternative approach, for example in the form of role-play-based simulations with trained actors representing typical professional activities in environments of reduced complexity. We have developed such a performance-based assessment format for physics teacher education, following the concept of Objective Structured Teaching Examinations (OSTE), as used in medical education. The developed OSTE prototype consists of seven short simulation-based assessments, reflecting four areas of teachers' professional competence (Instruction, Assessment, Pedagogy and Innovation) that form a 90-minute examination course. To investigate prospective physics teachers' perceptions of such an assessment format in terms of its suitability as a summative examination procedure, we piloted the OSTE prototype with N = 54 physics prospective teachers from five German universities using short questionnaires. The results show that participants perceived the OSTE as authentic and relevant. However, they also highlight the need for adequately designed new learning opportunities to prepare for such examinations, which should be integrated into teacher education programmes.

Keywords: teacher education, assessment, examination, simulation, core practice

Background

Prospective teachers often find it difficult to apply the knowledge acquired during their university studies in the classroom and often feel that their studies do not adequately prepare them for future professional practice (Tynjälä & Heikkinen, 2011). This gap between theory and practice in academic teacher education has been the subject of much research. However, the influence of the assessment or examination procedures used in teacher education on this gap is rarely considered.

The Role Of Assessments For Learning

Assessments serve various purposes. Assessment results are used for certification, which has implications for candidates' further study and careers (summative assessment). Furthermore, feedback on assessments can inform students about their performance and thus support them in achieving future learning goals (formative assessment). Hence, according to the model of Constructive Alignment, assessments – including formal examinations – learning objectives and learning activities need to be aligned in such a way that they form a coherent learning process (Biggs & Tang, 2011). Therefore, in teacher education, assessments must be designed in such a way that prospective teachers acquire the necessary skills to become good teachers.

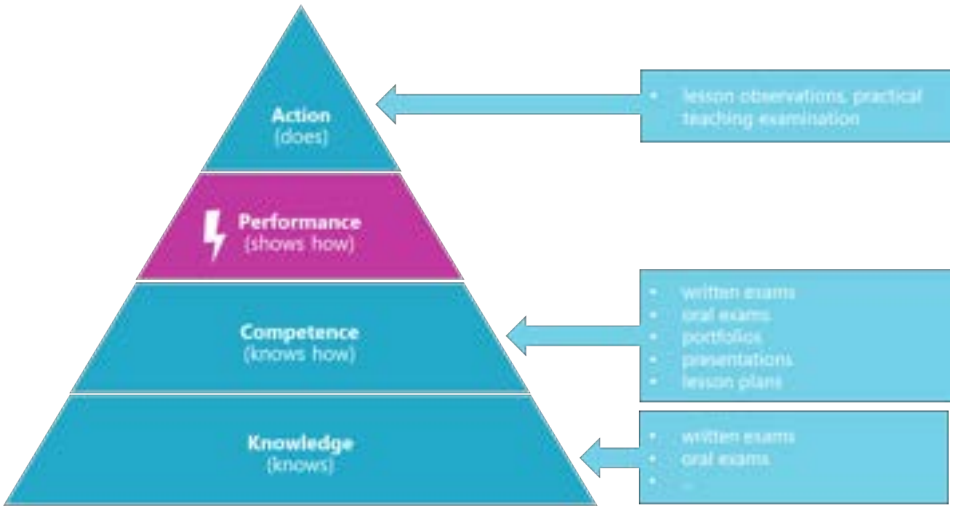
Research in higher education indicates that students' perceptions of assessment procedures or formats have a variety of effects on how they learn and on their course choices (Struyven et al., 2005). Various aspects of assessments have been found to be particularly important. For example, the fairness of an assessment is critical, meaning the perception of fair evaluation and the

opportunity for the candidates to demonstrate their actual capabilities (Sambell, 1997). Fairness of an assessment is related to its perceived transparency, referring to clear expectations and evaluation criteria (Drew, 2001). A key factor, particularly in teacher education, is how authentic an assessment is perceived to be. The authenticity of an assessment relates to how relevant it is perceived to be for the intended learning objective, and its alignment with the professional activities of teachers. Additionally, it refers to whether the content and procedure of an assessment are considered to be authentic (Gulikers et al., 2008). Students tend to choose more in-depth learning strategies to meet the intended learning goals if they perceive an assessment to be more authentic (Villaroel et al., 2021). However, the typical assessments formats used in teacher education programmes rarely reflect later professional activities.

Assessment-Gap In Teacher Education

For a more detailed analysis of assessment formats, we use Miller's (1990) framework for clinical assessment (Figure 1). Although it was originally developed for medical education, it can also be adapted for teacher education.

Figure 1. Typical assessment formats used in teacher education.



The framework differentiates between four levels of assessment depending on which learner dispositions or abilities are focused on. Assessments at the first level (level of knowledge) focus on prospective teachers' declarative knowledge (e.g. content knowledge). Typical formats for assessing this knowledge are written or oral exams. At the second level (level of competence), assessments focus on the procedural knowledge that prospective teachers need to know in order to perform typical professional tasks (Verloop et al., 2001). Alongside written and oral exams, typical formats include portfolios, term papers and, particularly in teacher education, written lesson plans. Assessments at the third level (level of performance) focus on prospective teachers' performance. The focus of this level is on performance, in the sense that prospective teachers can demonstrate their ability to carry out specific professional tasks in a standardised, lower-complexity setting. In contrast, assessments at the fourth level (level of action) focus on prospective teachers' actions under the full complexity of the field. There is a kind of 'assessment gap' between the testing of knowledge on the one hand and professional action in the full complexity of the classroom on the other. While typical formats such as classroom observations are frequently used in teacher education programmes at the fourth level, formats at the third level are scarce. This points to an assessment gap that mirrors the broader theory–practice divide in teacher education.

Addressing The Gap: Performance-Based Assessments

Assessment formats are needed that represent typical professional activities in settings of reduced complexity (approximations of practice, Grossman, 2021). Such assessment formats have long been established in medical education. In these assessments, typical professional tasks (e.g. conducting a clinical interview) are simulated under standardised conditions, often in role-play-based simulations with trained actors. To assess medical educators' teaching and communication skills, several such simulated tasks are also combined in so-called Objective Structured Teaching Examinations (OSTE) (Fakhouri & Nunes, 2019). An OSTE typically consists of a series of 10-15-minute simulation-based assessments that are completed as a coherent examination course. Comparable performance-based assessment formats have rarely been used in teacher education, particularly in science teacher education. However, simulation-based learning approaches are sometimes used for training purposes (e.g. Dotger et al., 2010) or in research projects (e.g. Kulgemeyer & Riese, 2018). Previous findings suggest that prospective teachers positively evaluate such simulations, and especially role-playing formats, as realistic practice and perceive them as authentic and motivating (cf. de Coninck et al. 2019). However, there is seldom evidence of their suitability as an assessment format in teacher education. Therefore, we analysed prospective teachers' perceptions of performance-based examination procedures based on the exemplary case of a specific OSTE developed for Physics Teacher Education.

An OSTE Prototype For Physics Teacher Education

We developed a prototype of an OSTE with the aim of assessing performative aspects of the professional competence of prospective physics teachers (Blömeke et al., 2015). It consists of seven 10–20-minute stations designed aligned with the four areas of competence (Instruction, Assessment, Pedagogy and Innovation) defined in the German National Standards for Teacher Education (KMK, 2022). Following the core practices approach (Grossman, 2021), each station assesses a single isolated core practice. Some stations have a more pedagogical focus, and others focus more on practices specific to physics teachers and were developed based on previous work (e.g., Feser, 2019; Kulgemeyer & Riese, 2018). In terms of content, the stations focus on mechanics. The task and the corresponding response format of the stations vary: the OSTE includes simulated conversations with trained actors as well as simulated video calls on a laptop and stations that must be completed entirely in writing. An overview of all simulated scenarios is described in Table 1.

Participants complete each station in turn, though this order varied from person to person. A complete examination course takes approximately 90 minutes, including short breaks, to fit into the standard schedule of typical courses in German teacher education. All stations follow the same procedure:

1) The participant familiarises with the context of the station by using the material provided (e.g. vignette with background information, standardised auxiliary materials).
2) The participant prepares for the task in a short preparation time.
3) The participant carries out the task.
4) The participant moves on to the next station.

Performance at each station is assessed using standardised coding rubrics by trained raters. In our pilot study, different forms of data were collected depending on the response format, which provided the basis for the performance evaluation. The simulated conversations with actors were videotaped and transcribed afterwards. In the simulated video calls, participants spoke their

answers into a headset microphone. These were audio-recorded and also transcribed. The written answers were processed in the same way as traditional forms of assessment.

Table 1. OSTE-Overview

	Scenario/Task	Response
Instruction		
Station 1: Lesson planning	Participants are asked to fill in the blank in a given lesson plan for a physics lesson by devising a suitable experiment on Newton's Third Law.	written
Station 2: Analysing physics lessons	During a field placement, a fellow prospective teacher asked for feedback on his teaching. Participants therefore have to reflect on and provide feedback on short sequences of videotaped instruction.	simulated video call
Station 3: Explaining a physical phenomenon	Participants are asked to explain to a student why motorcycle accidents are more likely to happen on bends after rain.	simulated conversation (one actor)
Assessment		
Station 4: Student counseling	Participants have to conduct an individual counselling/consultative meeting with a student who is repeatedly disruptive in class	simulated conversation (one actor)
Station 5: Evaluating students' answers in a test	Participants are given two answers to a physics test on acoustics written by students and must evaluate them using provided criteria.	written
Pedagogy		
Station 6: Mediating a conflict between two students	Two students have gotten into a conflict during a break. Participants have to mediate in order to resolve or defuse the conflict.	simulated conversation (two actors)
Innovation		
Station 7: Collaborative lesson development	Participants are asked to discuss the suitability of a lesson analysis tool with a colleague for potential use in professional development.	simulated video call

Objectives

Using the OSTE prototype as an example, we investigated prospective teachers' perspectives on such a performance-based assessment format, which was adapted from medical education. The following research question was investigated.

How do prospective teachers perceive an OSTE prototype for physics teacher education in terms of its suitability as a possible examination procedure?

In particular, we focused on prospective teachers' views of authenticity, cognitive involvement and perceived academic preparation for the OSTE.

Method

We tested the OSTE with eight groups of pre-service teachers at five German universities in 2024. The sample consists of N = 54 prospective physics teachers (gender: 64.8% male, 35.2% female). At the time of the pilot study, they were, on average, in their sixth semester (M = 6.2, SD = 4.1).

44.4% of the participants already had experience teaching mechanics in schools at the time of the test (e.g. through their mandatory field experiences or working as substitute teachers).

After finishing each station, participants completed a short questionnaire with five-point Likert items about their perceptions of the station in terms of authenticity (3 items, example: *"I think the situation described is authentic."*) and cognitive involvement (3 items, example: *"I have immersed myself in the situation."*). The internal consistency of both scales was sufficient for all stations (authenticity: $0.73 < \alpha < 0.88$, cognitive involvement: $0.80 < \alpha < 0.87$). The participants were also asked how well their studies had prepared them for each station (1 item, *"I feel that my studies have prepared me well for the station."*). At the end of the whole OSTE, they completed a questionnaire covering demographic information and an overall rating of the OSTE prototype using six-point Likert items (see Table 3). We were able to conduct follow-up interviews with four participants to gain deeper insights into their perspectives and to enrich the quantitative data.

Results

Evaluation Of The Individual Stations/Scenarios

Table 2 shows the descriptive results regarding perceived authenticity, cognitive involvement and preparedness.

Table 2. Descriptive results – individual stations (range: 0 to 4, theoretical mean: 2).

Station	Authenticity		Cognitive Involvement		Preparedness	
	M	SD	M	SD	M	SD
Station 1: Lesson planning	2.73	0.91	3.13	0.74	2.45	1.01
Station 2: Analysing physics lessons	2.84	0.83	2.98	0.81	2.31	1.06
Station 3: Explaining a physical phenomenon	3.18	0.79	3.36	0.67	2.23	1.02
Station 4: Student counselling	3.35	0.61	3.42	0.59	0.90	1.04
Station 5: Evaluating students' answers in a test	3.35	0.61	3.40	0.58	1.75	1.04
Station 6: Mediating a conflict between two students	3.47	0.61	3.31	0.61	0.87	1.07
Station 7: Collaborative lesson development	2.93	0.93	3.01	0.76	1.71	1.27

Regarding the evaluation of the individual stations, Station 5 (Evaluating students' answers in a test) and the simulated conversation in Station 6 (Mediating a conflict between two students) in particular generated a high level of cognitive involvement and were perceived as highly authentic. The stations with simulated video calls and Station 1 (Lesson planning) were perceived as slightly less authentic, but cognitive involvement was still comparably high. In terms of trends, stations involving actors were perceived as more authentic. In comparison, stations closer to the lower assessment levels in Miller's (1990) framework were perceived as less authentic. On average, however, perceptions of each station were above the theoretical mean. Participants were highly cognitively involved in each station. Box plots of data for authenticity and cognitive involvement are also shown in Figures 2 and 3 to illustrate the differences among participants more concisely. Overall, students felt that their studies had done little to prepare them for the tasks set at the examination stations. They felt most prepared for tasks relating to instruction, which are found in stations 1 to 3. For more pedagogical core practices reflected in Station 4 (Student counseling) or Station 6 (Mediating a conflict between two students) most of them felt not prepared at all.

Figure 2. Perceived authenticity of the individual stations – Boxplots.

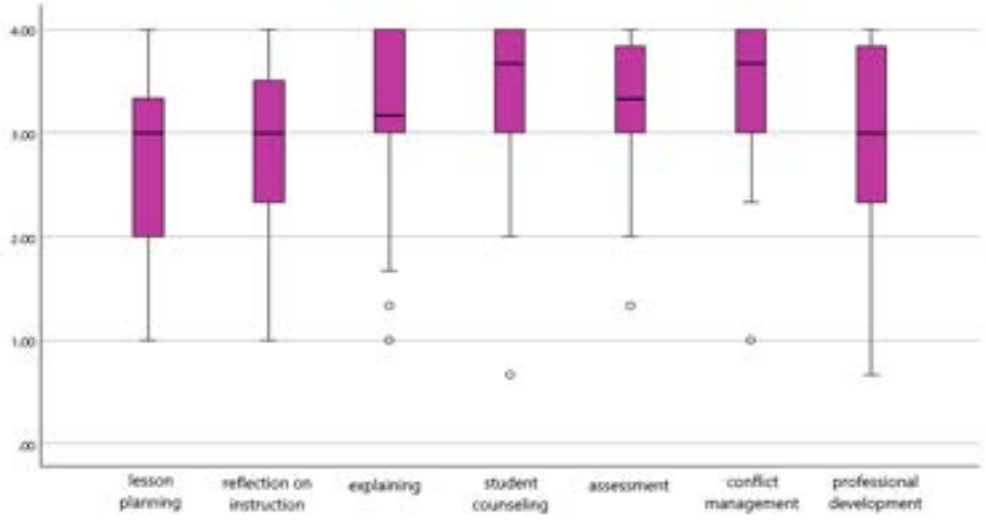
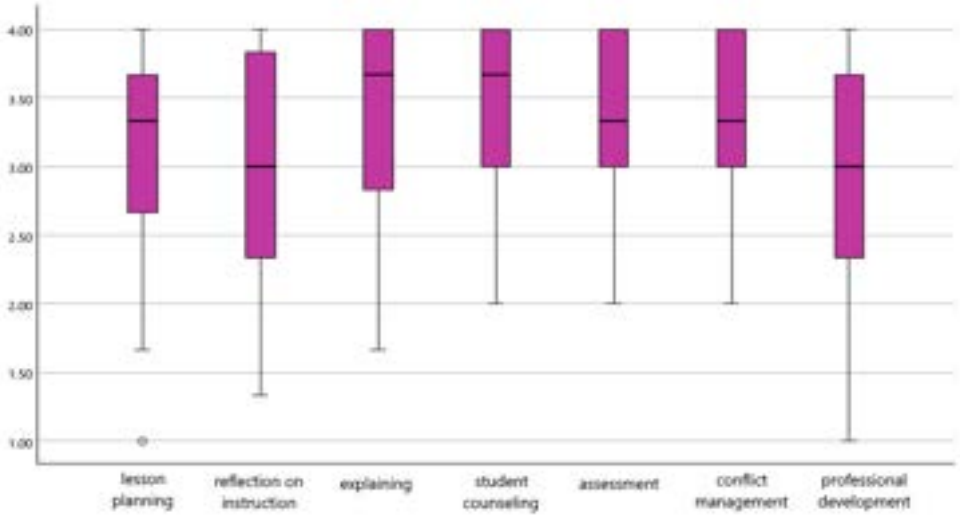


Figure 3. Perceived cognitive involvement in the individual stations – Boxplots.



Evaluation of the whole OSTE prototype

Table 3 shows the descriptive results regarding the overall assessment of the OSTE prototype.

Table 3. Descriptive results – overall evaluation (theoretical mean: 3.5).

Items	M	SD
"Such an examination course assesses what is relevant for my future career as a teacher"	5.35	0.71
"You can prepare well for such an examination course"	3.57	1.04
"In such an examination course it is easy to compare the performance of different students"	3.81	1.11
"An examination course like this reflects authentic practices of the teaching profession"	5.41	0.71
"You can plan your preparation well for such an examination course"	3.81	1.09
"An examination course like this assesses what is relevant throughout teacher education"	5.20	1.02

The results are positive in terms of their suitability as a possible examination format but also point to the challenges of the still unfamiliar format. Specifically, participants felt that the OSTE

prototype reflects authentic professional core practices of physics teachers and assesses what is relevant to their future profession. On the other hand, the participants were less positive about the possibility of preparing well for such an examination format and the comparability of students' performance in the OSTE prototype.

These quantitative results are also reflected in the interviews. For example, one participant pointed out that the OSTE prototype covers relevant professional skills.

> "Also zum einen, dass man Fachwissen halt zum Beispiel einem Schüler nahbringen kann. Das ist ja eine Kompetenz, die eigentlich sehr wichtig ist, aber die so bis jetzt in keiner Prüfung bei mir eigentlich drankam würde ich sagen. [Well, for one thing, you can teach a student content knowledge. That's a competency that's actually very important, but I would say that it hasn't really come up in any of my exams so far.]"

The time pressure aspect of the OSTE prototype was also considered to be an appropriate representation of the professional demands placed on teachers.

> "Ich habe erst gedacht, dass es so ein bisschen auch negativ [...] ist, dadurch, dass man ja so schnell 'switchen' muss zwischen diesen einzelnen Stationen, dann habe ich aber gedacht, wenn man später in dem Beruf ist wird es nicht anders sein. [At first, I thought it was a bit negative [...] because you have to switch between these different stations so quickly, but then I realised that it won't be any different when you're working in the profession later on.]"

However, the interviews also suggest that prospective teachers feel less prepared for performance-based assessments compared to traditional assessment formats.

> "So als Prüfungsformat finde ich das besser, aber ich persönlich fände die mündliche Prüfung für mich schöner, weil ich mich da halt besser drauf vorbereiten könnte, weil ich eher weiß, was da drankommt. [I think that's a better examination format, but personally I would prefer the oral exam because I could prepare for it better, as I have a better idea of what to expect.]"

Discussion

Overall, the OSTE prototype is perceived by participants as very relevant and authentic to teachers' professional practice, similar to the findings for simulation-based learning scenarios reported, for example, by de Coninck et al. (2019) and Wildgans-Lang et al. (2022). Based on the results, it can be assumed that the OSTE would be accepted as an examination procedure by prospective physics teachers, if they are adequately prepared for this innovative assessment format during the course of their studies. Adapting teaching approaches and learning environments is clearly necessary if performance-based assessments such as the OSTE are to be integrated into teacher education programmes, following the concept of Constructive Alignment (Biggs & Tang, 2011). This would not only help pre-service teachers to prepare for the assessment but also make the assessment format more transparent. The successful pilot tests at five different universities also suggest that the results are likely to be generalisable across different specific curricula.

However, it is difficult to determine the extent to which students consider the procedure to be fair. In our pilot study, we could not test the OSTE as a summative assessment, as this would necessitate modifications to the formal examination procedures at each university. The students therefore did not experience the OSTE prototype as a high-stakes assessment, but they knew that it was an initial trial designed to gather their perspectives on the format. The evaluation would probably have differed in some respects if their performance had actually been graded, which

would have had a greater impact on their future studies. Therefore, further trials under high-stakes pressure conditions are necessary. Despite its high transformative potential, the implementation of an OSTE as a summative examination procedure requires more resources than traditional examination formats (e.g. trained actors, sufficient rooms). Careful con-sideration should therefore be given to the stage of teacher education at which such an OSTE can be integrated most effectively. This also remains an open question for future research.

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Dealing With Students' Misconceptions In A Virtual Reality Classroom In Pre-Service Teacher Training

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Pre-service teacher training at universities faces the challenge of combining theoretical knowledge and practical experience. In order to bridge this gap, enormous efforts are made to create training situations that are as close to reality as possible, for example by inviting classes to universities or conducting role plays. Modern technologies, such as virtual reality (VR) classrooms, offer innovative opportunities to simulate immersive training situations while saving on personnel and time resources. In addition, VR-based training scenarios can be reproducible and analysable. Pre-service teachers can gain experience in dealing with virtual students in a protected environment and afterwards analyse their own actions and reactions. The study presented here aims to use a VR classroom to train future chemistry teachers. The focus is on dealing with student misconceptions. While the pre-service teachers in the VR classroom can react as they would in a real classroom, a coach manipulates the virtual students and thus the teaching situation. The purpose of this study is to determine whether this VR-based training helps pre-service chemistry teachers recognize and respond to common misconceptions about combustion.

Keywords: Pre-Service Teacher Education, Virtual Reality

Introduction

Balancing theory and practice in pre-service teacher training remains a significant challenge in higher education. In response, several German states, require pre-service teachers to complete an internship semester. In the run-up to this practical experience in school, the university seminars aim to prepare pre-service teachers for teaching situations as realistically as possible.

Placing prospective teachers in an immersive environment and training them in that environment through the use of VR offers new opportunities. Although research on the application of VR in teacher education is still in its early stages, initial findings suggest that VR classrooms can have a positive impact on aspects of teacher preparation such as presence in the classroom (e.g., Wiepke, 2022). The aim of the study presented here is to utilize the potential of a VR classroom for the training of future chemistry teachers. One focus is on dealing with students' misconceptions in a virtual discussion.

Theoretical Framework

VR In Pre-Service Teacher Training

Research into the potential applications of VR environments for pre-service teacher training is not yet very advanced. At the same time, immersive VR media are increasingly being integrated into educational contexts and studies to analyse their potential benefits (Wiepke & Heinemann, 2024). Initial studies indicate positive effects on the behaviour of pre-service teachers, but also highlight the great need for further development and research. The advantages of using a VR classroom as a teaching simulation include the immersive experience and reproducibility (Wiepke, 2022). In addition, VR classrooms provide the opportunity to experience and practice teaching in a safe environment (Lugrin et al., 2016). Therefore, there is potential in exposing pre-service teachers to a virtual teaching situation, that allows them to analyse their own behaviour and repeatedly engage in the same or a similar teaching situation.

The complexity of a teaching situation can be a major challenge, especially for those just starting out in the profession. Classroom management is therefore an important aspect of pre-service teacher training (Evertson & Weinstein, 2013). For this reason, previous research on VR classrooms has focused on classroom management training. To this end, Lugrin et al. (2016) developed a VR classroom that is used in university seminars. In this setting, pre-service teachers are deliberately placed in stressful situations in order to promote and analyse classroom management skills. The results of the study indicate that the system is suitable for university education, that acceptance by pre-service teachers is high and their assessment is positive (Lugrin et al., 2016).

Students' Misconceptions

The fact that students often use every day beliefs, which are not always scientifically based preconceptions in the chemistry classrooms has been empirically investigated many times (e.g., Horton, 2007; Schmidt et al., 2007). It has also been shown that teachers and pre-service teachers know little about misconceptions or how to deal with them (e.g., Gabel, 1999; Uhren et al., 2013).

For this reason, there are established concepts for the training and further education of (future) chemistry teachers that address the diagnosis and handling of students' misconceptions in chemistry lessons (e.g., Marohn, 2008). Rohrbacher-Lochner and Marohn (2018) developed and evaluated a seminar for pre-service chemistry teachers, in which the pre-service teachers received theoretical input on student misconceptions, planned a lesson on this basis and carried it out with invited classes at the university (Rohrbacher-Lochner & Marohn, 2018). But running real classes at universities requires extensive planning and is very time consuming. At this point, the use of a VR classroom in university education can be resource-saving. In addition, it offers the advantages of reproducibility and comparability of teaching situations. The study presented here focuses on the handling of student misconceptions in a virtual classroom discussion with the topic of 'combustion'.

Method

The study takes place as part of an obligatory course for all chemistry teacher students in the master's program. In the subsequent semester, these pre-service teachers will participate in an internship semester. During the seminar sessions at university, various topics are dealt with in preparation for the practice, such as lesson planning and teaching methods. One seminar session explicitly addresses students' misconceptions, their diagnosis, and possible forms of response. At the end of the semester, the pre-service teachers participate in the VR classroom individually. They are placed in a given teaching situation on the topic of 'combustion' and their task is to lead a class discussion to analyse the experiment 'combustion of iron wool'. In this experiment, the iron wool is weighed before and after combustion. The chemical reaction of the combustion causes the iron wool to react with the oxygen in the air and is heavier after the reaction. The explanation for the increase in weight requires knowledge of chemical reactions. Concerning this, there are a number of examined misconceptions (e. g., Horton, 2007).

In this study, the VR classroom developed by the University of Potsdam is used (e.g., Wiepke, 2022; Huang et al., 2021). It is designed for two users: a pre-service teacher, who is trained and a coach supervising the training session. Using a VR head-mounted display and controllers, the pre-service teacher enters a virtual classroom with 30 virtual students (Figures 1 and 2). The virtual students are controlled by the coach via a web interface, which shows the seating arrangement of the virtual classroom so that each individual virtual student can be controlled. In order to simulate the classroom discussion, possible student responses were anticipated in advance and recorded in a path diagram. Empirically proven misconceptions on the topic of

'combustion' were included in these statements. The coach assigns the pre-service teacher's statements and reactions to one of three categories: From *"Notices and responds to students' misconceptions in a way that promotes a meaningful class discussion"* to *"Does not react to students' misconceptions and does not promote a meaningful class discussion"*. By following the paths in the diagram, the coach selects a suitable student answer.

Figure 1. Pre-Service Chemistry Teacher with VR Head-Mounted Display.



Figure 2. Virtual Students in the VR Classroom (Participant's Perspective).



Research Questions

One focus of this study is to explore the potential of the VR classroom in terms of how pre-service chemistry teachers deal with students' misconceptions:

Q1) How do pre-service teachers respond to students' misconceptions in a classroom discussion in the VR classroom?

Q2) How do pre-service teachers evaluate the teaching situation in the VR classroom?

To address the research questions, a qualitative study was conducted. Therefore, video recordings were made of the pre-service chemistry teachers during their training in the VR classroom as well as screen recordings of the virtual students including the web interface. In addition, the pre-service teachers answered a questionnaire directly after the training. This questionnaire consists of five questions, three of which are answered on a three- or four-point Likert scale and two of which are open-ended. The questions that use a Likert scale could also be answered with *"not able to assess"*. The focus of the questionnaire is on the subjective impression after training in the VR classroom. One week later, individual interviews were conducted. The interview guideline focuses on the experiences in the VR classroom, self-perception and their own assessment of how they dealt with students' misconceptions. Furthermore, excerpts from the

video recordings were used to reflect on the conversation. The interview transcripts were used to answer research questions Q1) and Q2).

First Results

Eight pre-service teachers participated in the first trial in February 2025. They only reacted visibly to the misconceptions in 23% of cases, which is very low. Interestingly, prospective teachers usually responded immediately with an explanation, rather than, for example, asking follow-up questions or involving other students in the conversation. There seems to be room for improvement, particularly since classroom discussions based on misconceptions provide great learning opportunities (Sommer et al., 2022).

The evaluation of the questionnaire, which was completed directly after the training, shows that the pre-service teachers described the experience in the VR classroom as consistently positive. In one of the open-ended questions, five pre-service teachers mentioned that they needed a short time to get used to the VR classroom, but then quickly found their way around. Half of the pre-service teachers reported that they had identified all the misconceptions, while the other half assumed that they had not recognized all the misconceptions (Likert scale: *recognized all misconceptions, recognized not all misconceptions, recognized none misconceptions*). This is particularly remarkable because the pre-service teachers only responded to the misconceptions mentioned in a quarter of the cases. When asked how confident they felt in spontaneously reacting to student statements, half of the pre-service teachers responded with *not confident*, three with *confident* and one was not able to assess (Likert scale: *very confident, confident, not confident, not confident at all*). Seven of the eight pre-service teachers rated the usefulness of VR for pre-service teachers as at least high (Likert scale: *very high, high, medium, low*). These results were confirmed by the guided interviews conducted one week after the training. Five of the pre-service teachers once again emphasized the benefits for their own development and the environment's intuitive handling of. However, they would like to have more opportunities to interact with the virtual class, e.g., working together on a blackboard. The interviews also revealed that the pre-service teachers were unsure how to deal with the misconceptions mentioned during the conversation, which is consistent with the results described above.

Discussion and Outlook

Overall, these first results presented are only preliminary. Nevertheless, these results suggest that the pre-service teachers' attitude towards the training in the VR classroom is positive and that the training is considered helpful for professional development (Q2). In addition, the first trial resulted in extensions to the path diagram to enable the coach to react more flexibly to the students' impulses and foster a more fluent classroom conversation. However, it became clear that pre-service teachers rarely visibly respond to the aforementioned misconceptions and still have limited conversation prompts (Q1). Clearly, there is still great potential for developing their conversation skills here, which will be addressed in subsequent seminars together with the per-service teachers.

The next iteration of the study will investigate whether the training leads to improved identification of misconceptions and better dialogue management in class discussions. For this reason, the training will be carried out twice in the following study. In order to achieve improvements in dialogue management, the first training session will be analysed in more detail together with the pre-service teachers and after that, they go through a second training in the VR classroom. In addition, we plan to develop a second VR classroom that deals with the subject of electrochemistry.

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Primary Pre-Service Teachers' Professional Identity Development For Teaching Climate Change

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Given the complexity of the climate crisis, preparing pre-service teachers to teach Climate Change as a multifaceted topic is essential. However, pre-service teachers are unprepared to integrate this multifacetedness into their teaching. This study investigates how pre-service teachers develop their professional identities during a 12-week seminar on Climate Change Education at a southern European university. The participants in the study were 29 primary pre-service teachers who had participated in activities related to Climate Change content and Climate Change competencies (Normative Competence, Anticipatory Competence, System Thinking, Strategic Competence, and Interpersonal Competence). Simultaneously, the pre-service teachers, divided into seven groups, designed step-by-step teaching materials on Climate Change that included Climate Change competencies. Data were collected through autobiographical texts, teaching materials, reflection journals, and final interviews, and qualitative analysis methods were utilised. The findings indicate that Climate Change Teacher Education should support pre-service teachers by fostering self-awareness and equipping them with teaching strategies to build students' Climate Change Competencies. Participants recognised their competence in teaching Climate Change and explored widely used teaching strategies. Moreover, this process enhanced their self-recognition as competent Climate Change teachers, reinforcing their confidence in integrating Climate Change into their future teaching practices. These findings contribute to the growing discourse on Climate Change Teacher Education, emphasising the benefits of identity-focused approaches that empower pre-service teachers to engage students meaningfully in sustainability and climate action.

Keywords: Science Teacher Identity, Teacher Education, Climate Change

Introduction

Climate Change is a 21st-century challenge that affects the natural environment, society, the economy, and health (IPCC, 2023). Therefore, the climate crisis is not only an ecological threat but also a moral and educational challenge that demands action across all sectors of society. Climate change is a complex system shaped by interacting natural processes and human activities, making it difficult to define, predict, and address with single solutions (Lehtonen et al., 2018; Miani et al., 2025a; Peters & Tarpey, 2019). It is often described as a "super-wicked problem" because interventions can meet resistance or produce unintended consequences. Scientifically, climate change involves non-linear interactions, feedback loops, and uncertainty across interconnected Earth subsystems, which demand an interdisciplinary understanding (Miani et al., 2025a). Socially, it functions as a polarised socioscientific issue, involving ethical dilemmas, justice concerns, and emotional dimensions. These features challenge education, where fragmented curricula and content transmission often fail to support holistic systems thinking and transformative competencies (Eilam, 2022; Sezen-Barrie et al., 2025). Engaging multiple perspectives supports systemic reasoning about drivers and solutions (Cantell et al., 2019; Höhle & Bengtsson, 2023), while future thinking helps learners connect present decisions to uncertain but plausible trajectories (Miani et al., 2025b).

Consequently, addressing the climate crisis requires interdisciplinary and systemic approaches, as well as cooperation among diverse stakeholders (Lehtonen et al., 2018; Miani et al.,2025a).

This makes it vital for Climate Change Education to develop key skills that improve climate literacy and prepare students to be future citizens capable of addressing climate challenges (USGCRP, 2024). These key skills, known as sustainability or climate change competencies, are a) Normative Competence, b) Anticipatory Competence, c) Systems Thinking, d) Strategic Competence, and e) Interpersonal Competence (Wiek et al., 2011), with Scientific Inquiry playing a key role in building and applying these skills (Taurinen et al., 2024).

Building students' key competencies for climate literacy requires teachers who can effectively incorporate them into their teaching. However, teachers encounter various challenges in implementing Climate Change Education. These challenges arise from fragmented knowledge of content and a lack of confidence in managing the inherent uncertainty of climate science (Waldron et al., 2019). Consequently, it becomes difficult to address the complexity of the phenomenon in the classroom and to link scientific content with its societal, ethical, and emotional dimensions (Drewes et al., 2018; Shea et al., 2016). Additionally, several studies indicate that teachers often feel unprepared (Ennes et al., 2021; Waldron et al., 2019) and do not see themselves as competent climate change educators (Ratinen, 2013). This limited professional self-recognition is associated with hesitation in fostering values and agency within their teaching role (Hestness et al., 2014; Timm & Barth, 2021) and is influenced by teachers' personal experiences, attitudes, values, and beliefs regarding climate change (Bascopé et al., 2025; Leite, 2024; McNeal et al., 2017).

Addressing these challenges requires teacher education to move beyond emphasising content knowledge and pedagogical strategies and adopt more comprehensive approaches. Effective Climate Change Teacher Education should not only strengthen teachers' understanding of scientific concepts and ability to design inquiry-based, interdisciplinary learning environments, but also connect this knowledge to the broader social, economic, and ethical dimensions of the climate crisis (Brandt et al., 2019; Cantell et al., 2019). Furthermore, teacher education must offer opportunities for teachers to reflect on their own experiences, values, and beliefs, recognising that positionality fundamentally shapes professional practices and agency. When such elements are integrated, teacher education becomes a transformative space for developing an identity through which teachers see themselves as competent and responsible educators, capable of linking scientific understanding with moral purpose and social engagement (Menon, 2020).

Nevertheless, few studies focus on Climate Change Teacher Education (Rousell & Cutter–Mackenzie–Knowles, 2020), and even fewer invest in teachers' beliefs, values, and attitudes as part of their professional growth. While research highlights the importance of pre-service teacher education beyond scientific content alone (Ennes et al., 2021; Hestness et al., 2014; Waldron et al., 2019; Zangori et al., 2017), there are very few empirical studies that examine teacher training and professional development related to climate change content alongside teachers' beliefs, values and attitudes, and their interaction with environmental, societal, and economic factors (e.g. Brandt et al., 2019; Kriewaldt & Jun Lee, 2023; Waldron et al., 2019).

To address these issues, we propose using the lens of Teacher Identity (Avraamidou, 2014a) in teacher education through the concept of Climate Change Teacher Identity. Climate Change Teacher Identity (CCTI) is crucial for preparing teachers to address the scientific, interdisciplinary, and socio-political demands of Climate Change Education. Teaching climate change requires more than content knowledge and pedagogical techniques: teachers must integrate knowledge, skills, attitudes, and values to help students develop sustainability competencies and navigate complex, uncertain futures (Felix & Clayton, 2025; Howell & Allen, 2019). Building on science teacher identity research (Avraamidou, 2014a), CCTI extends science teacher identity by foregrounding urgency, ethics, emotions, and civic responsibility, positioning

teachers as facilitators of systems thinking, futures thinking, and value-based inquiry (Eilam, 2022; Miani et al., 2025a). Despite growing work on Climate Change Teacher Education, coherent identity-based frameworks, especially in primary education, remain limited.

We conceptualise CCTI through Carlone and Johnson's (2007) three dimensions: competence, performance, and recognition, while recognising that emotions, values, and context shape all three (Avraamidou, 2019; Nation & Feldman, 2022). Competence involves an evidence-based understanding of climate systems and their interactions with the environment, society, the economy, politics, and ethics. Performance refers to how teachers enact this competence through language, representations, and pedagogical tools, including engaging uncertainty and controversy. Recognition concerns seeing oneself, and being seen by others, as a legitimate climate change educator, supported through reflective questions about past, present, and future teacher selves.

Based on the above, this study focuses on the development of the Climate Change Teacher Identity of primary education pre-service teachers as a lens on how pre-service teachers learn and develop during a university seminar on Climate Change Education. The research question that guides this investigation is "How do the dimensions of Primary pre-service teachers' Climate Change Teacher Identity depict during the design of teaching materials on climate change complexity?"

Methods

Research Design And Participants

To address the research question mentioned above, we examined the development of primary pre-service teachers' Climate Change Teacher Identity. All 29 participants took part in a 12-week university seminar on Climate Change Education at the Department of Primary Education in the University of Crete, organised into 7 groups of 4 to 5 students each. In this study, the first author held a double role of a trainer and researcher.

The sessions of this seminar included the following activities:

Reflection on learning experiences in formal and informal environments and values about Climate Change (Session 1): The pre-service teachers had to recall and reflect on their past learning experiences, attitudes, and values related to Climate Change, and share those experiences with their group. Based on their reflections, the participants developed an autobiographical text in which they expressed the aforementioned past experiences in more detail.

Introduction to the scientific content (Session 2): In this session, the pre-service teachers became familiar with Climate Change content by exploring its impacts using real data, hands-on and video experiments, and models and simulations.

Engagement with activities for Climate Change Competencies (Sessions 4-10): The pre-service teachers participated in activities related to the complexity of Climate Change through physics experiments, discussed inclusivity in proposed solutions for Climate Change through a role-playing game, and envisioned themselves in IPCC future scenarios. For these sessions, they wrote three reflection journals and a text in which they imagined themselves as future Climate Change teachers. During this session, they became more familiar with innovative teaching methods proposed by the literature.

Teaching Material Development and Implementation (Sessions 2-12): During these sessions, the pre-service teachers designed, developed, and implemented teaching materials based on climate change competencies, utilising tools such as CoRes (Hume & Berry, 2010) and continuous feedback from the trainer and researcher in this study. The teaching material developed by the

participants was rich, including hands-on experiments, group activities that enhance students' decision-making skills and agency (role-playing games and actions), and artefacts. The implementation took place in the university's science centre.

Data Collection

Data were gathered from autobiographical texts, teaching materials, reflection journals, and a final semi-structured interview. The autobiographical texts offer insights into pre-service teachers' personal experiences, attitudes, and values towards climate change, providing space to express their Self-View as future climate change educators. The reflection journals served both as sources for pre-service teachers' Competence and Self-View. The teaching materials on the other side provided insights into pre-service teachers' Competence and Performance, serving as a means for participants to embody their knowledge and skills related to climate change, as well as their perceptions of a climate change educator's role. Finally, the final interviews served as a form of data triangulation.

Data Analysis

Given the exploratory nature of the study and the small number of participants, we employed qualitative content analysis methods (Mayring, 2014). To answer our research question, we conducted a top-down and bottom-up analysis of autobiographical texts, reflection journals, and teaching materials, focusing on pre-service teachers' Climate Change Teacher Identity. For that, we utilised Carlone & Johnson's framework (2007) to develop a category system for the Climate Change Teacher Identity dimensions. More specifically, Competence was examined through pre-service teachers' knowledge and understanding of Climate Change Complexity (e.g. systems thinking, uncertainty, multiplicity, etc.). Performance was examined in terms of the extent and manner in which PSTs expressed climate change complexity through their designed teaching materials (e.g., representations, tasks, inquiries, decision-making structures). As far as Recognition that regards how the pre-service teachers see themselves and are seen by others, we decided to focus on the first part since the majority of them have not enrolled in practicals yet, and as a result, they haven't yet any reflections on how their students or other teachers are seeing them. Based on that, we focused on pre-service teachers' self-view, which was examined through pre-service teachers' perceptions of themselves and their roles as climate change educators, including how they described their responsibilities, doubts, and ethical/value orientations. Table 1 presents the categories and subcategories derived from this analysis.

Table 1. Categories and Subcategories for Climate Change Teacher Identity

Categories	Subcategories
Competence	Resistance in the nature of complex systems Challenges in managing multiple perspectives Managing Social Aspects Systemic Approaches
Performance	Implement Feedback loop Implement Interactions between subsystems Implement Linear approaches Implement Social/Financial/Ethical implications
Self-View	Activist Optimist Sceptic Inspiring

Results

Across the dataset, participants showed the development of Climate Change Teacher Identity across all three identity dimensions. Below, we present findings organised by Competence, Performance, and Self-View, then highlight interactions among these dimensions.

Competence

Preservice teachers showed developing competence by clearly identifying aspects of climate change complexity and reflecting on the difficulty of communicating those ideas to children. One participant from Group 7 highlighted the challenge of explaining the disproportionate impacts of a seemingly small temperature rise and also recognised personal involvement in the issue:

"I believe the most difficult aspect to negotiate with primary school students will be helping them realise that just a 2-degree increase in temperature can be so destructive and understanding how we, ourselves, contribute to that rise."

This excerpt reflects competence in two ways: (1) recognising that climate change impacts are non-linear and counterintuitive, and (2) linking the scientific phenomenon to human systems and agency.

Another pre-service teacher from Group 1 pointed to the complexity introduced by political-economic structures in sustainability-related practices (in this case, recycling), indicating awareness that climate-related issues cannot be reduced to individual behaviour alone:

"What I think would be the most difficult to explain to students is how recycling works in each region, and why these changes depend on factors like quantity, cost, etc. Because they don't fully understand the political and economic issues that complicate the situation."

Here, competence includes understanding variability across contexts and recognising socio-economic aspects as part of the system.

Pre-service teachers also engaged with uncertainty and epistemic questions about predictability. One excerpt shows a participant from Group 3 negotiating what counts as a scientifically acceptable explanation, resisting embracing the nature of complexity: "Here, even though it's not stated that something supernatural intervenes in the system, chance seems to me as such. So, it doesn't align with my own understanding of science."

While another pre-service teacher from Group 5 reframed unpredictability as a matter of limited means rather than chance in interplay with deterministic laws:

"Perhaps if the conclusion were that we simply can't yet predict its evolution because we don't have the necessary means, it would be easier for me to accept."

This shows increasing skill in distinguishing epistemic uncertainty (limits of measurement and modelling) from non-scientific explanations, which is essential for teaching complexity responsibly. However, it also reveals a strong resistance to embracing the inherent complexity of nonlinear systems and to interpreting their evolution solely through deterministic laws.

Performance

Performance was apparent in how pre-service teachers designed learning sequences and chose phenomena that could act as "entry points" into complex system reasoning. The dataset included teaching materials on ocean acidification, glacier melting, and their implications for biodiversity. Finally, one teaching material approached sustainable mobility as a solution to climate change through hydrogen-powered cars.

In these materials, the pre-service teachers attempted to represent causal chains and feedback relationships (e.g., emissions → ocean chemistry changes → ecological consequences), integrate observable phenomena and modelling and hands-on experimentation, and build decision-making tasks that connect scientific understanding with choices and values.

However, pre-service teachers varied in the degree of sophistication in their teaching materials. While a common pattern was the use of concrete contexts (oceans, glaciers) to support students' reasoning and understanding of climate science, some materials approached these concepts by emphasising only one-way interactions (e.g., the impact of increasing CO2 concentration in the oceans and its effect on ocean biodiversity, without addressing the feedback loop influencing the atmosphere). On the other hand, Groups 1, 2, 6, and 7, which demonstrated greater competence in embracing complexity and managing multiple perspectives in their teaching, succeeded in designing materials that familiarised students with the various drivers of the climate system, as well as the societal aspects that interact with it.

An exception to these two categories is Group 4, which consisted of pre-service teachers facing multiple challenges in scientific content. This group spent time during the seminar familiarising themselves with the scientific content but paid less attention to integrating complexity into it.

Self-View

Self-View appeared in pre-service teachers' reflections on the teacher's role, especially their responsibility to support meaningful action, cultivate values, and serve as role models.

One pre-service teacher described an intention to emphasise practical actions so students can immediately see positive impacts and develop daily environmental awareness:

"Finally, I would like to place greater emphasis on simple and practical actions that students can undertake, so that they can immediately recognise the positive impact of their choices and develop environmental awareness in their daily lives."

This reflects self-recognition through an action-oriented teaching stance, in which the teacher's identity is linked to empowering students.

Another pre-service teacher articulated a deeper tension on how to foster enduring values rather than short-term compliance, and how the teacher's own behaviour and role modelling become part of climate change teaching:

"How can I convey to my students an attitude and a way of life that they will follow throughout their lifetime and not just in the short term? How will they fully embrace the principles and values of a climate-literate citizen? I believe that attitudes and values are matters cultivated daily, not merely through a single educational scenario. What kind of role model do you, as a teacher, provide for your students?"

This excerpt illustrates recognition as a stance of reflective, ethically aware identity. Pre-service teachers are not only asking "Can I teach this content?" but also "Who must I be, and how must I live, to teach this credibly?"

This collection of excerpts represented all groups except again Groups 3 and 5, who appear to be sceptics of certain proposed solutions related to climate change, as well as of the effectiveness of the teacher's role in the current economic status quo.

An example of this scepticism is represented in the excerpt below: "The discussion about green growth doesn't satisfy me, because I see that this plan is also being carried out without a central strategy, and probably not in order to improve our everyday lives."

Interactions Among Climate Change Identity Dimensions

Across the seven cases, the data suggested that competence, performance, and self-view were not isolated. Instead, pre-service teachers' materials and reflections showed interactions consistent with identity scholarship (e.g., Beijaard et al., 2004; Keiler, 2018).

Competence And Performance

Pre-service teachers who clearly expressed complexity and uncertainty tended to design tasks that incorporated system relationships, contextual constraints, or systems thinking rather than simple cause-and-effect narratives.

Performance And Recognition

As pre-service teachers developed and improved teaching materials, recognition was evidenced through responsibility statements (e.g., emphasising daily actions, role modelling, values). Designing for practice prompted reflection on what it means to be a climate change teacher.

Recognition And Competence

Recognition concerns (e.g., wanting to promote values responsibly) sometimes led pre-service teachers to seek more thorough explanations and more careful framing of the concepts of the climate system and the societal drivers within it.

These interactions support the argument that Climate Change Teacher Identity is co-constructed through iterative engagement with content, pedagogy, and professional positioning.

Discussion

This study provides empirical insights into how pre-service teachers learn and develop as they formulate their professional identities by reflecting on their prior experiences, values, and attitudes toward climate change as they learn to teach it. By adapting Carlone and Johnson's (2007) framework, we conceptualised identity not simply as confidence or attitude but as a dynamic interplay of (a) competence in complexity-focused reasoning, (b) performance through designed teaching practices, and (c) self-view through self-positioning and legitimacy.

The findings align with the broader literature, which shows that teachers experience fragmented knowledge and uncertainty as obstacles, struggle to transform climate science into teachable material, and integrate the value-oriented nature of climate change teaching. Yet the results also point to noticeable shifts when the pre-service teachers begin to treat complexity as an opportunity to expand their teaching rather than a reason to avoid the topic. They selected phenomena that enable complexity representations and engaged in reflective recognition of the challenges and obstacles to negotiating these representations with their students.

Our findings highlight the critical role of Climate Change Teacher Education in shaping teachers' positionality and equipping them with the necessary teaching strategies to address complex topics like Climate Change (Nation & Feldman, 2022; Tolppanen & Kärkkäinen, 2022). By fostering self-awareness, pre-service teachers became more confident in teaching Climate Change content, utilising their strengths to integrate diverse pedagogical approaches. This process also enhanced their self-recognition as competent climate change educators prepared to respond to the challenges of the climate crisis. A central implication is that teacher education can support climate change teaching not only by "adding more content" but by designing learning experiences where pre-service teachers engage explicitly with complexity and uncertainty, iteratively translate this into teaching materials, and reflect on positionality, ethics, and the teacher's role.

Implications For Climate Change Teacher Education

Considering that attitudes, values, and personal experiences shape the teaching climate for climate change, it is crucial to examine how teachers' professional identities develop and are reshaped over time (Nation & Feldman, 2022; Tolppanen & Kärkkäinen, 2021). The Climate Change Teacher Identity framework proposed above highlights that competence, performance, and self-view are co-constructed through teachers' biographies and the learning environments

they encounter. Therefore, Climate Change Teacher Education should go beyond disseminating content knowledge and pedagogical strategies to create conditions in which pre-service teachers can reconstruct themselves as climate change educators. Evidence from climate change-focused professional development suggests that identity shifts are strongly supported when teachers are given sustained opportunities to reflect on their positioning, values, and experiences alongside learning about climate change content and pedagogy (e.g., Nation & Feldman, 2022; Tolppanen & Kärkkäinen, 2021; Zen et al., 2024).

Accordingly, climate change teacher education should foreground structured identity work integrated with practice: sustained self-awareness and self-reflection on teaching trajectories through autobiographies, reflective journals, and prompts that engage questions such as "Who am I as a teacher?", "How did I become this kind of teacher?", and "Who do I want to become as a teacher?" (Avraamidou, 2019), so that pre-service teachers can trace changes in their competence, performances, and self-view over time.

These identity-oriented activities should be integrated into opportunities for learning, designing, and experimenting with teaching methods that are common in Climate Change Education. Such methods include investigating local phenomena, engaging in systems-thinking tasks, exploring futures-thinking activities, and participating in value-focused discussions. This allows pre-service teachers to see themselves as climate change educators and to renegotiate their identity claims through tangible classroom practices (Felix & Clayton, 2025; Nation & Feldman, 2022; Sezen-Barrie et al., 2025). Overall, Climate Change Teacher Education should be intentionally designed as a space where pre-service teachers both learn how to teach about climate change and develop into climate change teachers. This can be achieved through combining autobiographical exploration, ongoing reflection, and multimodal self-representations with rich pedagogical experiences. These experiences broaden competencies, enable new ways of performance, and foster recognition as climate change educators.

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Exploring Pre-Service Primary Teachers' Pedagogical Content Knowledge Of Interdisciplinarity In Science And Mathematics

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This study examines the interdisciplinary pedagogical content knowledge (IPCK) of pre-service primary teachers enrolled in a two-year master's program in Primary Education (1st to 6th grades), with a specialization in Mathematics and Sciences. The main objective was to investigate changes in their IPCK regarding interdisciplinarity between science and mathematics following participation in a lesson study. Data were collected through an open-ended questionnaire administered in two phases, before and after the lesson study. The questionnaire aimed to capture the specificity of pre-service teachers' understanding of interdisciplinarity by exploring their conceptualizations and the examples of activities they proposed to promote the integration of science and mathematics.

The results indicate that, before the lesson study, pre-service teachers held a limited view of interdisciplinarity, characterized by uneven connections between the two areas. There was a significant emphasis on interdisciplinarity through knowledge to be explored, with less attention given to the processes. Mathematics was mainly integrated through data processing within sciences activities. Furthermore, only a few participants viewed interdisciplinarity as a meaningful integration, where both disciplines collaborate to support one another, thereby enabling unique learning experiences. After the lesson study, the findings suggest that most pre-service primary teachers changed their IPCK towards a more comprehensive perspective on interdisciplinarity in science and mathematics.

Keywords: Interdisciplinarity in science and mathematics; Pre-service primary teachers; Lesson study; Pedagogical content knowledge

Introduction

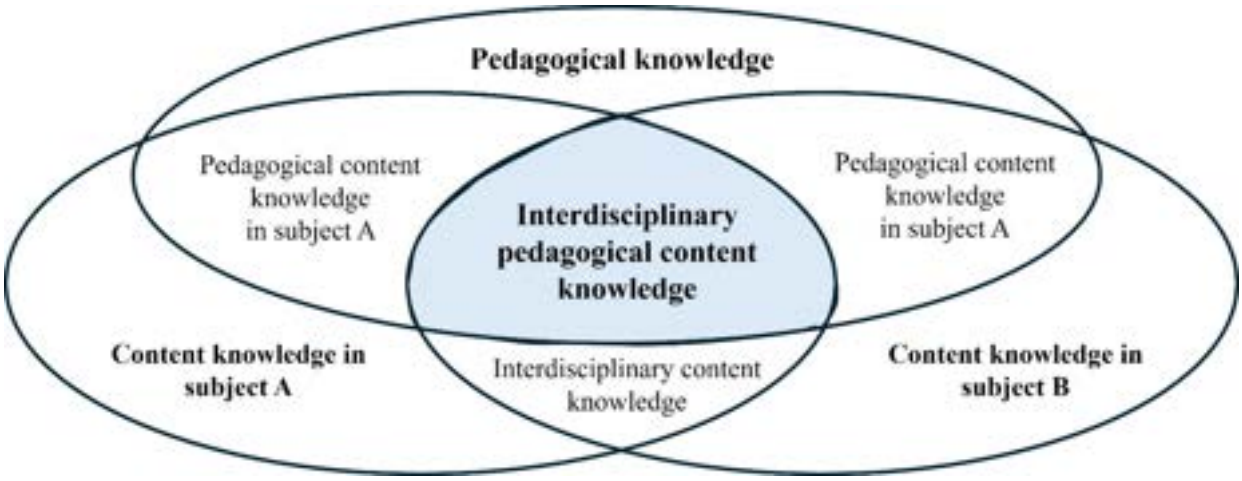
Future teachers should be able to make connections between different disciplines. An interdisciplinary approach encourages deeper understanding overtime, inter-relating different topics or subjects (OECD, 2019). That implies careful planning in how and when the topics of each subject will be explored, to promote connections between them.

However, the implementation of interdisciplinarity in schools faces problems of different kinds (e.g. Johnson & Czerniak, 2023). The interdisciplinary work between science and mathematics will always involve the mobilization of disciplinary knowledge from, at least, these two disciplines and depends upon teachers' pedagogical content knowledge (PCK) of each discipline (Ríordáin et al., 2015) and their possible intersections, denominated interdisciplinary pedagogical content knowledge (IPCK) (An, 2017) (Figure 1). According to An (2017),

> interdisciplinary pedagogical content knowledge (IPCK) is the specific capacity for teachers to accomplish the following: (1) work with interdisciplinary considerations that include an understanding of the representation of concepts using themes across curriculum boundaries; (2) apply pedagogical methods and interdisciplinary themed activities in addressing content areas from multiple subjects simultaneously; (3) identify knowledge connections within and between particular subjects, and develop lessons based on such

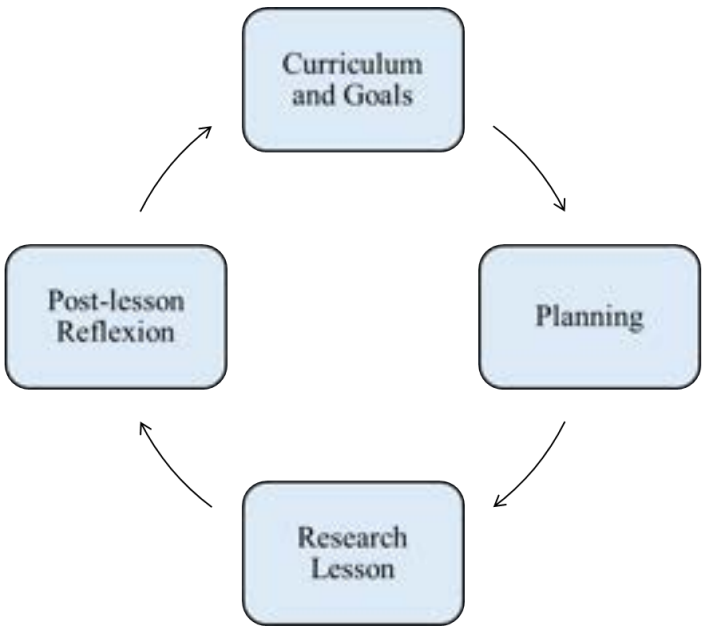
connections; and (4) employ knowledge of how interdisciplinary explorations can be developed as a part of an instructional process wherein students link existing knowledge across curricula, while presenting that new knowledge through contexts from multiple subjects. (p. 239)

Figure 1. Graphic representation of interdisciplinary pedagogical content knowledge (IPCK) (An, 2017, p. 239).



A way to support teachers practice professional development regarding interdisciplinarity is through lesson study (Lewis, 2009; Murata, 2011; Tomkelski et al., 2022). The central framework of lesson study comprises four key moments: i) characterization of the context and definition of a goal for the development of the research lesson; ii) planning, that is, collaboratively designing a lesson on a specific curriculum topic through multiple sessions with a group of teachers; iii) research lesson, that corresponds to the implementation of the planned lesson in a classroom setting.; and iv) post-lesson reflection, when the group of teachers meets to discuss and reflect on the students' actions in the research lesson, based on observations recorded (Lewis, 2009; Murata, 2011; Tomkelski et al., 2022). Figure 2 presents the lesson study cycle constituted by four phases.

Figure 2. Lesson study cycle of the investigation (Adapted from Lewis, 2009; Murata, 2011; Tomkelski et al., 2022).



Lesson study provides opportunities for pre-service teachers to strengthen their understanding of content, pedagogy, and student learning, namely skills and knowledge in science and

mathematics education (e.g., Kraft et al., 2024; Martins et al., 2023). For instance, Martins et al. (2023) involved mathematics pre-service teachers in a lesson study and concluded that this process allowed them to refine their teaching strategies, leading to improved practice and a better understanding of how to promote students' mathematics reasoning. Kraft et al. (2024) in an extensive review of the literature on lesson studies in science teacher preparation programs concludes that lesson study is a transformative process, enriching pedagogical content knowledge.

This study explores the interdisciplinary pedagogical content knowledge (IPCK) of Portuguese pre-service primary teachers enrolled in a two-year master's program in Primary Education in Sciences and Mathematics. The main aim was to investigate changes in pre-service primary teachers' PCK concerning interdisciplinarity in science and mathematics following their participation in a lesson study. The research is part of a broader project that aims to understand the dynamics of implementing interdisciplinary activities in science and mathematics. It involves pre-service primary teachers from two Portuguese higher education institutions, the Polytechnic Institutes of Setúbal and Lisbon, within the framework of lesson study.

Method

The participants were the whole class of the teaching master programme 2024/25, 11 pre-service primary teachers (8 females and 3 males, aged 22 to 35 years) enrolled in the courses "Didactics of Sciences", "Didactics of Mathematics" and "Teaching Practice in Primary Education". These are annual compulsory subjects in the second-year curriculum of the master's program in Primary Education (1st to 6th grades) with a specialization in Mathematics and Sciences, of the School of Education of Setúbal, Portugal. Prior to this program, the pre-service teachers had completed a three-year degree in Basic Education. The Didactics courses in both areas involved the exploration of different strategies for teaching science and mathematics and were used to support the planification of the research lesson, that was implemented during a seven-week internship in a 5th grade class (Teaching Practice).

During the first semester, the pre-service teachers completed a questionnaire to assess their pedagogical content knowledge of interdisciplinarity in science and mathematics, both before and after the implementation of the lesson study, after informed consent from all participants. The questionnaire was less structured, word-based and open-ended to capture the specificity of the situation analysed in this study (Cohen et al., 2007). This research instrument included four open-ended questions, as follows:

(1) Identify a curricular topic that integrates mathematics and sciences and can be approached interdisciplinarily in primary education (Key Stage 2).

(2) Indicate mathematics and sciences content that can be approached interdisciplinarily in the study of the topic you identified. You may use a diagram to illustrate the relationships between the content (Note: Students were allowed to consult official curriculum documents.).

(3) Provide examples of one or two interdisciplinary activities you would use to explore the topic, incorporating the previously mentioned content from both subjects. Specify the teaching strategies or methodological approach you would adopt in the classroom.

(4) If you have already planned or observed an interdisciplinary activity during previous internships or even during your school years as a student, describe the activity in question, highlighting its relevance.

The analysis of these questions involved content analysis, with the definition of categories and subcategories for analysis for each question, which were formed inductively based on data,

through an iterative process. Tables 1 and 2, which are presented in the results, show the categories and subcategories of questions 1 and 3 of the questionnaire, respectively, which were selected to present in this paper based on their relevance to the study.

For question 1, the following categories of analysis were defined: predominance of the subject area; and nature of the content. Question 2 included two categories: diversity of content; and nature of the content. In order to analyse the scope of responses to question 3, several categories of analysis were defined, namely: predominance of the subject area; curricular alignment; consistency between content and activity; type of activity; organization of work with students; teaching resources; and planned outputs. In the case of question 4, four categories of analysis were created: predominance of the subject area in the planned activity; predominance of the subject area in the activity experienced; relevance of the activity; and justification of the relevance of the activity.

Taking into account all the responses to the questionnaire, we also sought to analyse the concept of interdisciplinarity among students, considering two subcategories: comprehensive view and limited view (Table 3). The comprehensive view is related to the level of complete integration between the two disciplines, with the establishment of relationships between science and mathematics. In the limited view one of the disciplines, Mathematics or Science, predominates, but the other is also present, although in a supporting role.

The categorization of responses to each question was carried out by four researchers, authors of the paper, familiar with the theoretical framework of the study. In a joint meeting, the researchers discussed the main doubts in the categorization of data, and the entire analysis was reviewed. Disagreements were resolved through discussion until consensus was reached.

The lesson study process was structured within a single cycle with four main phases (Figure 2). In the first and second phases, during weeks one to four of the seven-week internship, the pre-service teachers worked collaboratively in groups to define the goals and plan a research lesson centred on an interdisciplinary activity in mathematics and sciences. This work was supported by the four higher education teachers, the researchers, in Didactics sessions. In the third phase, during weeks five to seven of the internship, while the other pre-service teacher from each internship pair taught the research lesson while the other pre-service teacher and one higher education teacher observed the lesson and collected data. The fourth phase, conducted after the internship, involved a group discussion about the planned and implemented lesson and a written reflection (one part produced collaboratively by the internship pair and another part developed individually).

Results and Discussion

Table 1 presents the results for question 1: Identify a curricular topic that integrates mathematics and sciences and can be approached interdisciplinarily in primary education (Key Stage 2), based on the responses of the 11 pre-service teachers (PST), who participated in both the initial and final applications of the questionnaire. The initial questionnaire, applied before the lesson study, shows that PST tended to select topics primarily focused on sciences. In these cases, the science topic served as the context for integrating mathematics, as illustrated by examples such as: “The Terrestrial Materials present in the region (determine the predominant type of terrestrial material in the region)” (PST 1) and “Biodiversity” (PST 3). After the lesson study, the responses reflected a greater emphasis on ensuring that, within the context of science activities, mathematical content is equally explored. The following example shows that situation: “Types of soil, soil properties, and powers of base 10” (PST 7). The absence of change in the category “nature of the contents” suggests that, despite improvements in disciplinary integration, pre-service teachers’ conceptions

of interdisciplinarity remain predominantly knowledge-oriented, possibly reflecting limitations associated with curricular structure and their still limited teaching experience.

Table 2 presents the results for question 3: Provide examples of one or two interdisciplinary activities you would use to explore the topic, incorporating the previously mentioned content from both subjects. Specify the teaching strategies or methodological approach you would adopt in the classroom for three selected categories. The initial questionnaire responses indicate a predominance of focus on the mathematics area. This may reflect the pre-service teachers' effort to make this subject explicit in the activity proposal, despite the curriculum topic focusing on science (as seen in question 1). After the lesson study, there was an increasing concern with integrating both subject areas in the interdisciplinary activity proposals.

Table 1. Pre-service teachers' responses to the question 1 of the initial and final applications of the questionnaire, before and after lesson study.

Categories	Subcategories	Number of PST (n=11)	
		InitialQ	FinalQ
Predominance of the subject area	Science	6	3
	Mathematics	1	0
	Both areas	4	8
Nature of the contents	Focus on knowledge	8	8
	Focus on process	0	0
	Knowledge and process	3	3

Table 2. Pre-service teachers' responses to the question 3 of the initial and final applications of the questionnaire, before and after lesson study.

Categories	Subcategories	Number of PST (n=11)	
		InitialQ	FinalQ
Predominance of the subject area	Science	4	2
	Mathematics	6	2
	Integration of both areas	1	7
Curricular alignment	Total	5	9
	Partial	6	2
	Without	0	0
Coherence between content and activity	Total	4	6
	Partial due to lack of explicitness	0	5
	Excluded due to lack of suitability	7	0
	Without	0	0

The results for the categories "curricular alignment" and "coherence between content and activity" (Table 2) reveal that there was an increased knowledge of the curriculum in the areas of mathematics and sciences, gained through direct involvement in the lesson study, which required an additional effort in a more detailed planning process – including curriculum analysis, task design, and reflection on learning. It is also important to note that this was the pre-service teachers' first teaching practice (internship) in primary education, specifically with 5th and 6th graders, which likely influenced their initial focus and subsequent development of their IPCK.

The results presented in Table 2 reveal a clear qualitative development in pre-service teachers' ability to design interdisciplinary activities. In particular, the disappearance of responses classified as "excluded due to lack of suitability" in the final questionnaire suggests a strengthened capacity to align interdisciplinary intentions with pedagogically coherent activities, an aspect associated with the collaborative planning, implementation, and reflection, characteristics of the lesson study process. At the same time, the increase in activities classified as "partial due to lack of explicitness" should not be interpreted as a regression, but rather as evidence of a growing awareness of the complexity involved in interdisciplinary planning. This pattern indicates that pre-service teachers proposed complex and ambitious integrations of mathematics and sciences, in some cases for the first time, although some proposals still required clearer articulation of the relationships between content and activity.

To illustrate the analysis, the following excerpt presents the activity proposed by one of the pre-service teachers in response to Question 3 of the final questionnaire. This activity demonstrates integration of both subject areas, total curricular alignment, and total coherence between content and the proposed activity:

> Analysis of Bottled Water Labels and Mineral Comparison
>
> Pupils, working in pairs, receive labels from different [and real] brands of bottled water and analyse the chemical information provided.
>
> In Natural Sciences, they discuss the importance of each mineral for human health and debate which type of water is most suitable for different needs (e.g. low-sodium water for people with high blood pressure).
>
> In Mathematics, pupils compare the decimal values shown on the labels, organize them in tables, and represent them on a number line.
>
> The methodological approach focuses on collaborative work and the use of concrete materials, promoting the integration of both subjects.
>
> (*PST 6, Final Questionnaire*)

Analysing the questionnaire responses as a whole, two conceptions of interdisciplinarity were identified: a comprehensive view and a limited view (Table 3). The initial questionnaire, applied before the lesson study, shows that most pre-service teachers (PST) proposed activities that considered an integrative topic, but mathematics supports science. Few PST view interdisciplinarity as a meaningful integration of mathematics and science, when the disciplines interact to support each other, allowing unique learning (An, 2017; Huntley, 1998). In the final questionnaire, evidence of IPCK development was observed. Most PST showed increased attention to balancing the presence of both subject areas, although integration was not always fully achieved, often occurring sequentially. Typically, the topic was selected from the science curriculum, with both areas explored within the activity.

Table 3. Pre-service teachers' conceptions of interdisciplinarity in the initial and final applications of the questionnaire, before and after lesson study.

Categories	Subcategories	Number of PST (n=11)	
		InitialQ	FinalQ
Conceptions of Interdisciplinarity	Comprehensive view (integration)	4	7
	Limited view (partial integration)	7	4

Conclusions

The findings indicate that the majority of pre-service primary teachers developed their interdisciplinary pedagogical content knowledge (IPCK) toward a more comprehensive perspective on interdisciplinarity in science and mathematics. This development was reflected in their increased ability to identify meaningful connections within and between both subjects, to design lessons grounded in these connections, and to deepen their understanding of the curriculum and how it can be coherently managed across subject areas. An initially limited conception of interdisciplinarity evolved into a more integrative perspective that encompasses the PCK of each discipline as well as their potential intersections (An, 2017).

Within the context of the project, the pre-service primary teachers participated in a lesson study, a formative process that emphasizes collaborative work in planning, observing, and reflecting on implemented lessons, with a focus on deepening their IPCK (Lewis, 2009; Murata, 2011). During this process, the pre-service teachers not only designed and implemented interdisciplinary tasks but also engaged in systematic reflection on their teaching experiences, identifying areas for improvement and refinement in their interdisciplinary practices. Across the different stages of the lesson study, reflection on the implemented lesson emerged as a particularly valued component of the training process, highlighting its central role in supporting the development of IPCK.

These findings should be interpreted in light of the study's limitations, namely the small number of participants, the focus on a single lesson study cycle, and the use of self-reported questionnaire data. Nevertheless, the results offer relevant insights into the potential of lesson study to support the development of IPCK in initial teacher education.

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Linking Pre-Lesson Content Representations And Post-Lesson Reflections: AI-Based Insights Into Context-Specific PCK Development

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Understanding pedagogical reasoning across the teaching cycle remains a central challenge in science education research, as lesson planning and retrospective reflection are typically examined using separate instruments and analytic frameworks. This contribution adopts a methodological perspective by linking Content Representations (CoRes) and written reflections as relational artefacts of pedagogical reasoning. Drawing on data from pre-service physics teachers during a teaching internship, embedding-based semantic similarity analyses are used to relate structured planning units from CoRes to segments of unstructured reflective texts. Instead of aggregating similarity scores or applying predefined coding schemes, the analyses retain the full relational structure and explore it using complementary representations, including similarity heatmaps and Principal Component Analysis. Exemplary case analyses illustrate how analytic design choices, such as reflection segmentation or modes of visualization, shape what becomes visible when planning and reflection are analysed in direct relation to one another. The contribution is exploratory and methodological: it demonstrates how relations between planning-related knowledge and retrospective reasoning can be made visible without evaluating teaching or inferring development or change in pedagogical content knowledge.

Keywords: Pedagogical Content Knowledge (PCK); Pedagogical reasoning; Content Representations (CoRes); Written reflection; Embedding-based text analysis

Introduction

Understanding pedagogical reasoning across the teaching cycle remains a central challenge in science education research, particularly because lesson planning and retrospective reflection are typically examined using separate instruments and analytic frameworks. Consequently, empirical research has rarely addressed how knowledge articulated during planning relates to how teachers' reason about their practice after teaching.

Within research on Pedagogical Content Knowledge (PCK), teachers' professional knowledge is understood as person-, topic-, and context-specific. Instruments such as Content Representations (CoRes) make planning-related PCK explicit, whereas written reflections provide access to retrospective pedagogical reasoning. Despite their widespread use, these instruments are rarely analysed in direct relation to one another, limiting insights into how articulated planning-related knowledge is taken up, recontextualized, or omitted in reflective discourse.

Recent advances in natural language processing enable new methodological approaches for exploring such relations. In particular, embedding-based semantic similarity analyses allow heterogeneous text-based artefacts to be related without relying on predefined coding schemes. This makes it possible to examine planning and reflection as relational data while refraining from evaluative or developmental claims.

Against this background, the present study explores how relations between CoRes and written reflections can be made visible by analysing them in direct relation to one another. Using AI-based semantic similarity analyses and focusing on exemplary cases, the study illustrates how different analytic representations foreground different aspects of planning–reflection relations.

The contribution is methodological and PCK-oriented: it demonstrates how planning and reflection can be linked analytically without evaluating teaching or inferring changes in PCK. By doing so, the study positions planning and reflection not as separate data sources, but as relational artefacts of pedagogical reasoning across the teaching cycle.

Theoretical Background

Pedagogical Content Knowledge And Pedagogical Reasoning

Pedagogical Content Knowledge (PCK) is widely regarded as a central component of science teachers' professional knowledge (Shulman, 1986, 1987; Van Driel et al., 1998; Van Driel & Berry, 2012; Loughran et al., 2006; Carlson et al., 2019). The Refined Consensus Model of PCK (RCM) provides a shared theoretical framework that distinguishes between different knowledge bases and emphasizes context-specific, enacted forms of PCK emerging in concrete teaching situations (Carlson et al., 2019).

Within the RCM, pedagogical reasoning is conceptualized as a cyclical process linking planning, teaching, and reflection (Alonzo et al., 2019). Planning and reflection are commonly associated with macro-level pedagogical reasoning, referring to articulated reasoning processes before and after teaching, whereas micro-level reasoning captures in-the-moment, often tacit decision-making during instruction. While macro-level pedagogical reasoning can be accessed through written artefacts such as lesson plans or reflections, micro-level reasoning remains empirically difficult to capture (Mientus et al., 2022).

In teacher education, practical phases are considered particularly relevant for PCK-related pedagogical reasoning, as they require pre-service teachers to articulate knowledge in planning and to retrospectively interpret their teaching experiences in reflection (Brouwer & Korthagen, 2005; Korthagen & Kessels, 1999). Accordingly, analysing artefacts of planning and reflection is a common approach to studying macro-level pedagogical reasoning. However, these artefacts are typically examined in isolation, leaving largely unaddressed how knowledge articulated during planning relates to retrospective reasoning after teaching.

Content Representations As Structured Planning Artifacts

Content Representations (CoRes) are a well-established instrument for capturing context-specific planning-related PCK in science education (Loughran et al., 2004, 2006). They are typically structured as tables in which teachers identify central "Big Ideas" of a topic and elaborate on them using guiding questions addressing different aspects of teaching (Sannert et al., 2025). Following the RCM, CoRes can be interpreted as structured articulations of different PCK facets, such as content knowledge (CK), pedagogical knowledge (PK), knowledge of students (KS), curricular knowledge (CuK), assessment knowledge (AK), and the learning context (Context) (Carlson et al., 2019; Mientus & Borowski, 2024); in the present study, these facets serve only as descriptive reference points rather than analytic coding categories. The PCK articulated in a CoRe is inherently person-, topic-, and context-specific (Chan & Hume, 2019).

In teacher education, CoRes are commonly used to support lesson planning and to externalize planning-related professional knowledge. Analytically, CoRes provide structured access to macro-level pedagogical reasoning before teaching, but do not capture how articulated planning-related knowledge is taken up or reconsidered after instruction.

Written Reflections As Retrospective Reasoning Artefacts

Written reflections are widely used to access retrospective pedagogical reasoning after teaching (Korthagen & Kessels, 1999; Poldner et al., 2014). They are typically unstructured free-text documents combining descriptive, evaluative, and affective elements. Reflective texts are

commonly analysed to study macro-level pedagogical reasoning, using qualitative, quantitative, or automated text-analytic approaches (Buckingham Shum et al., 2017; Ullmann, 2019; Wulff et al., 2022). However, reflective texts are often analysed in isolation, leaving open how retrospective reasoning relates to knowledge articulated during planning.

Linking CoRes and written reflections therefore offers a promising way to examine pedagogical reasoning across the teaching cycle, while posing methodological challenges due to the heterogeneous structure of the two artefacts. Together, CoRes and written reflections provide complementary access to macro-level pedagogical reasoning before and after teaching. Analysing them in relation to one another addresses a largely unexplored perspective in PCK-oriented research.

Methodological Approach

Research Context And Data Corpus

The study is situated in the context of pre-service physics teacher education during the teaching internship (Praxissemester) at the University of Potsdam. Practical phases in teacher education are considered a key setting for PCK-related pedagogical reasoning, as they require pre-service teachers to articulate professional knowledge in planning and to retrospectively interpret their teaching experiences. In this context, students are required to prepare, conduct, and reflect on their own lessons, thereby producing written artefacts associated with different phases of pedagogical reasoning.

Since the winter semester 2019/20, written self-reflections of pre-service physics teachers have been systematically collected as part of the ReFeed project (Mientus et al., 2021). Building on this data infrastructure, an additional preparatory component was introduced in the winter semester 2022/23: prior to teaching, students were asked to create Content Representations (CoRes) using a specially developed online environment. This resulted in paired datasets consisting of a CoRe as a planning artefact and a corresponding written reflection as a post-lesson artefact.

For the present study, data from six pre-service physics teachers were considered. Each participant produced three CoRe–reflection pairs related to self-taught lessons. After excluding incomplete cases, a total of 18 paired artefacts were available in the broader project. The present contribution draws on selected pairs for illustrative analysis. The aim is not statistical generalization, but the exploration of planning–reflection relations in person- and context-specific cases.

Instruments: Cores And Written Reflections

The Content Representation (CoRe) serves as the instrument for capturing planning-related professional knowledge prior to teaching. Following established practice (Loughran et al., 2006), CoRes are structured as tables in which central "Big Ideas" of a topic are elaborated using guiding questions. In the present implementation, these guiding questions were aligned with PCK facets specified in the Refined Consensus Model. Each table field can thus be treated as an articulation of context-specific professional knowledge related to content, pedagogy, students, curriculum, assessment, or learning context.

Written reflections constitute the complementary instrument for capturing retrospective pedagogical reasoning after teaching. Students produced free-text reflections on their lessons without a strict template, resulting in texts that vary in length, structure, and emphasis. The reflections combine descriptive accounts of classroom events with evaluative and affective elements and are consistent with common reflective practices in teacher education.

From a methodological perspective, the two instruments differ substantially in their degree of structure. CoRes provide segmented, planning-oriented representations of professional knowledge, whereas written reflections consist of continuous, unstructured text. Analysing relations between these artefacts therefore requires an approach that can relate heterogeneous text formats without reducing them to predefined categories.

Units Of Analysis And Segmentation

For the CoRes, each table field corresponding to a response to a guiding question is treated as an independent unit of analysis. This follows the internal logic of the instrument, as each field represents a coherent aspect of planning-related professional knowledge.

For written reflections, the default unit of analysis is the sentence. Sentence-level segmentation enables fine-grained mapping between planning units and reflective statements and supports detailed inspection of planning–reflection relations (Ullmann et al., 2019; Wulff et al., 2022). As reflective arguments may extend across multiple sentences, paragraph-level segmentation is additionally explored for illustrative purposes. Segmentation is treated as an analytic design choice, and its implications for interpreting semantic relations are explicitly addressed in the analysis.

Semantic Linking Of Planning And Reflection

To relate CoRes and written reflections, an embedding-based semantic similarity approach is employed. CoRe units and reflection segments are mapped into a shared semantic space using sentence embeddings derived from large language models. Semantic similarity between planning units and reflection segments is calculated using cosine similarity.

For each CoRe–reflection pair, all planning units are compared with all reflection segments, resulting in a similarity matrix that represents the relational structure between planning and reflection. Rather than aggregating similarity scores, the full similarity structure is retained for analysis and visualization. Heatmaps are used to illustrate local and sequential similarity patterns, while Principal Component Analysis (PCA) is applied to visualize the relative positioning of planning and reflection units in the shared semantic space. These representations serve an illustrative and exploratory purpose.

Analytic Focus And Scope

The analytic focus of the study is explicitly exploratory and methodological; the analyses neither evaluate teaching nor infer changes in PCK. Instead, they demonstrate how relations between planning and reflection can be made visible by analysing CoRes and written reflections in direct relation to one another. Accordingly, the study emphasizes exemplary case analyses rather than aggregate patterns. Selected CoRe–reflection pairs are used to illustrate how different analytic representations foreground different aspects of planning–reflection relations, such as the effects of segmentation choices or differences in global semantic overlap. The analyses are descriptive and intended to support methodological reflection on relational approaches to studying pedagogical reasoning in PCK-oriented research.

Analytic Strategy: Exemplary Case Analyses

The analyses presented in this study follow an exemplary and contrastive logic. Rather than aiming for systematic comparison or representativeness, selected CoRe–reflection pairs are used to illustrate how different analytic representations make different aspects of planning–reflection relations visible. The cases were chosen to highlight methodological contrasts, not to evaluate individual teachers or to establish typologies.

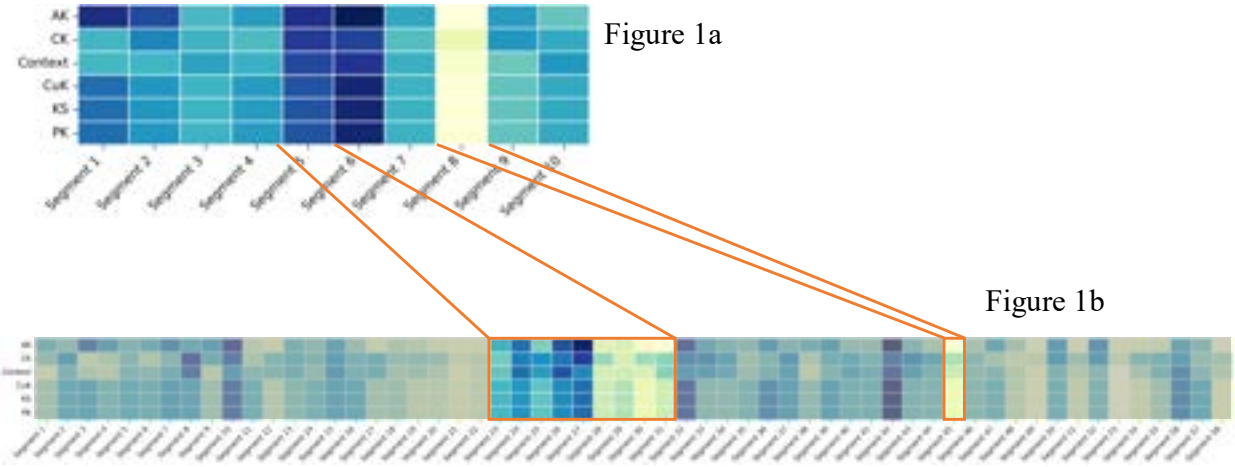
Two complementary analytic representations are employed. First, similarity heatmaps are used to examine local and sequential relations between planning units and reflection segments. These visualizations foreground how specific elements of articulated planning-related knowledge are semantically related to individual segments of the written reflection. Second, Principal Component Analysis (PCA) is used to visualize the global semantic configuration of planning and reflection units within a shared embedding space. This representation shifts the analytic focus from sequential relations to overall patterns of semantic overlap.

The two examples presented below are not intended as comparative cases in a strict sense. Instead, they serve as illustrative contrasts that demonstrate how analytic design choices shape what becomes visible when planning and reflection are analysed relationally.

Example 1: Effects Of Reflection Segmentation On Interpreting Planning–Reflection Relations

Figure 1 illustrates how analytic decisions regarding the segmentation of written reflections influence the interpretation of semantic relations between planning and reflection. Both heatmaps shown in Figure 1a and Figure 1b are based on the same CoRe–reflection pair. The only difference lies in the unit of analysis used for the written reflection: paragraph-level segmentation in Figure 1a and sentence-level segmentation in Figure 1b.

Figure 1. Effects of reflection segmentation on semantic relations between planning and reflection: similarity heatmaps based on paragraph-level (a) and sentence-level (b) segmentation of the same CoRe–reflection pair.



In Figure 1a, the written reflection is segmented into ten paragraphs. The vertical axis represents planning-related units from the CoRe, grouped by PCK-related facets, while the horizontal axis follows the reflection text paragraph by paragraph. At this level of aggregation, the heatmap suggests a relatively homogeneous pattern of semantic alignment. Several planning-related facets appear to co-occur across the same reflective segments, and only one paragraph shows minimal semantic proximity to the planning artefact.

When the same reflection is segmented at the sentence level (Figure 1b), a more differentiated pattern emerges. The reflection is now represented by 58 segments, revealing substantial variation in semantic similarity within paragraphs that previously appeared homogeneous. Sentences focusing on instructional actions and contextual constraints show higher semantic proximity to planning-related units, whereas affective or self-referential statements display markedly lower similarity.

This example demonstrates that segmentation is not a neutral preprocessing step, but a methodological lens that shapes how planning–reflection relations are interpreted. Paragraph-level segmentation foregrounds broader thematic alignment, whereas sentence-level

segmentation makes fine-grained variation within reflective discourse visible. Neither approach is treated as inherently superior; rather, the example illustrates how analytic choices affect what kinds of relations can be observed.

Example 2: Visualizing Semantic Overlap Between Planning And Reflection Using PCA

Figure 2 provides a complementary perspective by visualizing planning and reflection units in a shared semantic space using PCA. Whereas the heatmaps foreground local and sequential relations, the PCA shifts the analytic focus toward global patterns of semantic overlap and distance. Figures 2a and 2b show two illustrative CoRe–reflection pairs. The PCA represents a two-dimensional projection of high-dimensional embedding vectors; the axes themselves have no substantive interpretation and serve only to indicate relative semantic proximity.

In both figures, individual CoRe units are plotted as points and grouped by PCK-related facets, with ovals approximating the semantic regions spanned by each facet. Reflection sentences are plotted in the same space. The visualization highlights the degree to which reflective statements are located within or outside the semantic regions approximated by the planning artefact.

Figure 2. PCA-based visualization of the shared semantic space of CoRe planning units (grouped by PCK facets) and written reflection sentences for two illustrative planning–reflection pairs.

Figure 2a

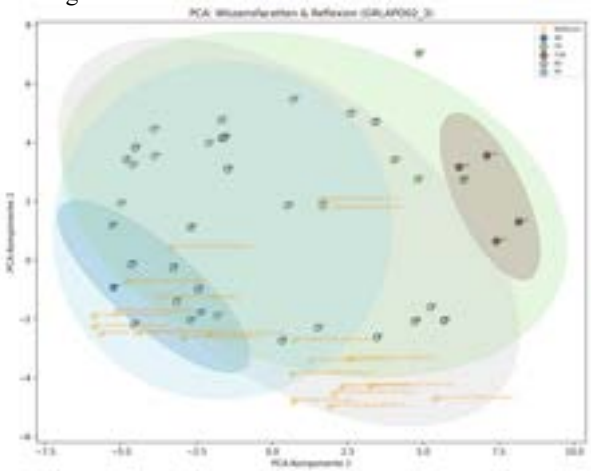
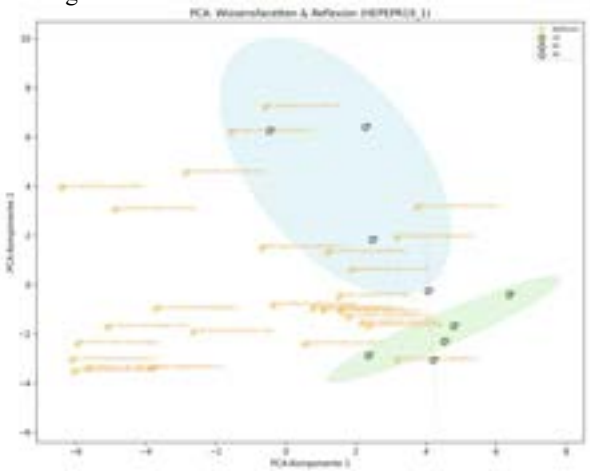


Figure 2b



In Figure 2a, reflection sentences are largely located within the regions spanned by the CoRe units. Descriptively, this configuration indicates a high degree of semantic overlap between planning-related knowledge and retrospective reflection. In Figure 2b, by contrast, several reflection sentences fall outside these regions, suggesting a lower degree of semantic overlap. These observations are reported descriptively and are not interpreted as indicators of teaching quality, completeness of planning, or professional development.

Across both cases, the PCA visualizations also illustrate that the apparent size and shape of planning-related semantic regions depend on properties of the underlying text material, such as length and elaboration. Consequently, PCA-based representations should be understood as heuristic tools for exploring global patterns of semantic overlap rather than as stable characteristics of individuals or artefacts.

Methodological Contribution Of The Exemplary Analyses

Taken together, the exemplary analyses illustrate how linking CoRes and written reflections enables a relational view of pedagogical reasoning that remains inaccessible when planning and reflection are analysed separately. The heatmaps foreground local and sequential relations, while the PCA visualizations provide a global perspective on semantic overlap. Importantly, the

examples show that different analytic representations do not reveal the same aspects of the data but selectively foreground different relations. The purpose of these analyses is not to derive generalizable findings, but to demonstrate the analytic potential and limitations of relational, embedding-based approaches for studying planning–reflection relations in PCK-oriented research.

Discussion

This contribution adopts a methodological perspective on pedagogical reasoning by treating lesson planning and retrospective reflection as relational artefacts situated at different points of the teaching cycle. Linking Content Representations and written reflections makes visible patterns of semantic alignment and non-alignment that remain inaccessible when each artefact is analysed in isolation. In this sense, the study extends instrument-specific approaches by foregrounding relations rather than isolated representations of professional knowledge.

The exemplary analyses resonate with theoretical conceptualizations of pedagogical reasoning as a cyclical process connecting planning, teaching, and reflection. Descriptively, instructional and contextual considerations articulated during planning tend to show higher semantic proximity to reflective statements than affective or self-referential passages. These observations suggest that different modes of retrospective reasoning relate differently to articulated planning-related knowledge. However, in line with the analytic scope outlined above, such patterns are not interpreted as indicators of learning, transformation, or quality of teaching; nor do the analyses provide access to micro-level reasoning processes or changes in PCK.

A central insight of the study is that analytic representations actively shape what becomes visible. Sequential similarity heatmaps foreground local relations along the progression of reflective texts, whereas spatial projections such as PCA highlight global patterns of semantic overlap. These representations are complementary rather than competing and underscore that relational analyses are not neutral windows onto pedagogical reasoning, but methodological lenses that emphasize different aspects of planning–reflection relations.

Limitations

The present study is subject to several limitations. First, the analyses are based on a small number of illustrative cases and are not intended to support generalization across individuals or contexts. The exemplary cases serve to demonstrate analytic possibilities rather than to establish stable empirical patterns.

Second, the observed relations are sensitive to methodological design choices. In particular, segmentation of reflective texts substantially affects the granularity and interpretation of semantic similarity, and PCA-based visualizations depend on properties of the underlying text material such as length, elaboration, and linguistic variation. These dependencies should be understood as characteristics of the analytic approach rather than as sources of measurement error.

Finally, the identified relations describe semantic proximity between planning and reflection, not learning outcomes, instructional effectiveness, or professional development. Developmental or evaluative interpretations would require additional data, triangulation with other methods, and longitudinal designs that are beyond the scope of this contribution.

Implications And Outlook

Despite these limitations, the study points to several implications for future research in science education. Methodologically, it illustrates how planning and reflection can be analysed as relational data without reducing either artefact to predefined categories or evaluative metrics.

This opens up exploratory research designs that focus on pedagogical reasoning across the teaching cycle rather than on isolated knowledge components.

Future work may systematically investigate how analytic decisions, such as segmentation strategies or modes of visualization, influence the interpretation of planning–reflection relations. Longitudinal designs could explore whether characteristic patterns of semantic alignment emerge over time and how they relate to instructional experience. Combining embedding-based analyses with qualitative interpretation may further clarify how different forms of retrospective reasoning connect to articulated planning-related knowledge.

At the same time, the approach should be understood as an analytic tool for making relations visible and inspectable, not as a validated measurement instrument. Its contribution lies in supporting methodological and theoretical reflection on how pedagogical reasoning can be studied relationally within PCK-oriented research, rather than in providing definitive interpretations of teachers' professional knowledge or its development.

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Technology And Pedagogy In Science Teacher Education: Promoting Teacher Candidates' Skills In Instructional Design And Learning Management Systems

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Two main models exist in teacher education programs to advance teacher candidates' (TCs') use of technology in teaching: 1) stand-alone courses on educational technology, and 2) infused model in which digital skills are integrated into teaching methods courses. In this paper, the authors present a collaboration that combines both approaches to promote technology use in science teacher education. We report on an assignment in the educational technology course that requires TCs to capitalize on their skill in science curriculum development to create an online learning module using learning management systems (LMS). This paper aims to analyse the content of TCs' developed online modules and present TCs' experiences in this assignment, with a focus on their skills in using LMS.

The authors adopt a qualitative approach. Participants are 10 TCs enrolled in both the educational technology course and the science methods course in the teacher education program at a university in Canada (secondary division). The authors analyse the online modules developed by the TCs and their reflections.

TCs' work and reflections showcase the positive impact of the training they received and the importance of the online module assignment in promoting their 1) pedagogical skills in science instructional design and 2) technological and pedagogical skills in incorporating digital tools into their lessons and using LMS. The assignment showed the importance of collaboration between educational technology and science education instructors to promote TCs' technological, pedagogical, and content knowledge. This research highlights the successes of professional development practices, especially ones focused on interdisciplinary collaborations in teacher education programs.

Keywords: Science teacher education, learning management systems, instructional design

Introduction and Objectives

Although stand-alone educational technology courses in teacher education allow teacher candidates (TCs) to develop proficiency in using digital tools (Roblyer & Hughes, 2019), they often lack integration with broader content knowledge and pedagogical skills (Estaiteyeh & Rong, 2026; Foulger et al., 2015). Alternatively, teacher educators can infuse technology in subject-specific courses like curriculum and methods courses in science teacher education programs to make technology training more relevant and practically applicable (Koehler et al., 2013). Indeed, Williamson et. al. (2023) emphasize collaboration among educators from different disciplines to foster a multidisciplinary method of technology integration in teacher education. In such infusion models, technology-supported learning strategies are taught, modeled, and practiced throughout the entire preparation program, with all teacher educators assuming responsibility for supporting science TCs' growth in teaching with technology (Sprague et al., 2022). However, time constraints and the need to cover a broad range of topics in science curriculum and methods courses limit science teacher educators from fully incorporating technology in their courses.

In this paper, the authors present a balanced approach that combines the stand-alone and infused approaches to promote technology use in science teacher education. The authors are two teacher

educators in a teacher education program in Canada who collaborated to complement each other's work in their respective courses. The first author teaches the stand-alone educational technology course while the second author teaches the science education course. In the educational technology course, TCs focus on the effective use of digital technologies in the classroom (Estaiteyeh et al., 2025). In the science methods course, TCs are introduced to curriculum design, teaching strategies, and assessment methods in secondary science education. We report on one of the assignments in the educational technology course that requires TCs to capitalize on their skill in science curriculum development to create an online learning module, all while advancing their skills in using learning management systems (LMS). Thus, this paper addresses the following research objectives:

1) Analysing the content of TCs' developed online modules.
2) Presenting TCs' experiences and reflections on this assignment, with a focus on their skills in using LMS.

Literature Review And Theoretical Framework

Preparing Tcs For Online Teaching And Using Learning Management Systems

With the increased prevalence of online learning and as per the lessons learned from teaching during the COVID-19 pandemic, there is a need to better equip TCs for technology-enhanced teaching practices, especially in online environments (DeCoito & Estaiteyeh, 2022; Barbour & Hodges, 2024). Success in online teaching depends on strong course design, appropriate material selection, effective pedagogical strategies, and clear communication with students and families alike (Fernández et al., 2017; Recker et al., 2013). Several studies in Canada have demonstrated the positive impacts of online teaching preparation and training on science TCs' readiness to support this teaching modality (Burns et al., 2020), especially in synchronous learning environments (Estaiteyeh et al., 2024). However, there is a gap in the literature on preparing TCs for asynchronous online teaching and instructional design for virtual environments.

Furthermore, essential to the success of online teaching is the effective use of LMS, which is the platform that is primarily used in online environments. Thus, it is also important that TCs get sufficient training in using LMS, with a focus on student engagement and community building in online settings (Vivolo, 2019) and the use of a variety of interactive virtual resources (Smith et al., 2018). However, despite the importance of LMS, research on their use by TCs is limited. Accordingly, this research aims at advancing TCs' technological and pedagogical skills in using LMS to create effective online learning experiences for the students.

Technological, Pedagogical, and Content Knowledge (TPACK) Framework

This research is informed by the TPACK framework (Koehler et al., 2013). Shulman (1987) defines pedagogical content knowledge (PCK) as the capacity of a teacher to transform their content knowledge into forms that are pedagogically powerful yet adaptive to variations in students' abilities and backgrounds. Koehler et al. (2013) extend Shulman's PCK to integrate technology into teacher's pedagogy. In accordance with the technology infusion framework (Williamson et al., 2023) explained earlier, the authors emphasize how content, pedagogy, and technology interest across different courses in the teacher education program. In doing this work, TCs will capitalize on content and pedagogical knowledge acquired in science education courses to advance their pedagogical and technological knowledge fostered in the education technology course.

Methods

The authors adopt a qualitative approach (Creswell & Creswell, 2018) utilizing document analysis (Stake, 2020) to address the research objectives. Ten TCs (two males and eight females) participated in the study. Participants were enrolled in both the educational technology course and the science methods course in the first year of the two-year teacher education program at a university in Canada (secondary school teacher certification). The science education course ran for 24 weeks (Fall and Winter terms), while the educational technology course ran for 12 weeks in the Winter term.

Assignment Description

As part of the educational technology course, the instructor provided TCs with two workshops on online teaching and LMS features and functionalities. This training included providing relevant resources and tutorials, modelling by the instructor, and direct applications by TCs. Afterwards, the instructor introduced the online learning module assignment. This assignment built on what TCs had learned in the Fall term in the science education course (instructional design using the backward design model, student-centred teaching and assessment strategies). In this assignment, TCs worked individually or in pairs to design and develop an online learning module using Brightspace, the LMS adopted by most district school boards partnered with the University. The module should be developed for students in a class within the and focused on a specific concept within TCs' subject area (e.g., general science, biology, chemistry, physics). The module was planned by TCs to be completed mostly asynchronously by their prospective students. First, TCs completed the instructional design phase of the module. Then, they hosted their module on Brightspace LMS. In addition to developing the modules, TCs submited individual reflections on this assignment.

Data Sources and Analysis

The authors describe and analyse 1) the online modules developed by the TCs (total of seven modules) and 2) the individual reflections submitted by each TC (10 reflections). Sample reflection questions included: What did you benefit the most from this project? What challenges did you face (individual or group challenges)?

Data analysis adopted a deductive approach (Creswell & Creswell, 2018), using pre-determined themes (e.g., module contents, teaching and assessment staregies, incorporated digital tools, and LMS functionalities). The first author conducted the analysis, and the second author reviewed it by providing corrections. The two authors met to finalize the findings. This process of iterative and collaborative analysis was done to ensure the reliability and validity (Creswell & Creswell, 2018).

Results

Modules' Analysis

As shown in Figures 1 and 2, TCs used several LMS features and functionalities to host their module such as discussion boards, assignments, rubrics, quizzes, and digital publishing while attending to accessibility and inclusion guidelines. TCs were also able to augment their science lesson plans by incorporating digital tools such as multimedia, online simulations, virtual labs, and digital assessments. Although this was the first experience for almost all TCs in using LMS as teachers, their work on the online modules showed the positive impact of the provided training and the relevance of this assignment in preparing them for future use of the LMS software. Equally important, the assignment showed the importance of collaboration between educational technology and science education instructors to promote TCs' TPACK.

Figure 1. Screenshot of a module on DNA transcription showing the structure and flow of the module on Brightspace.

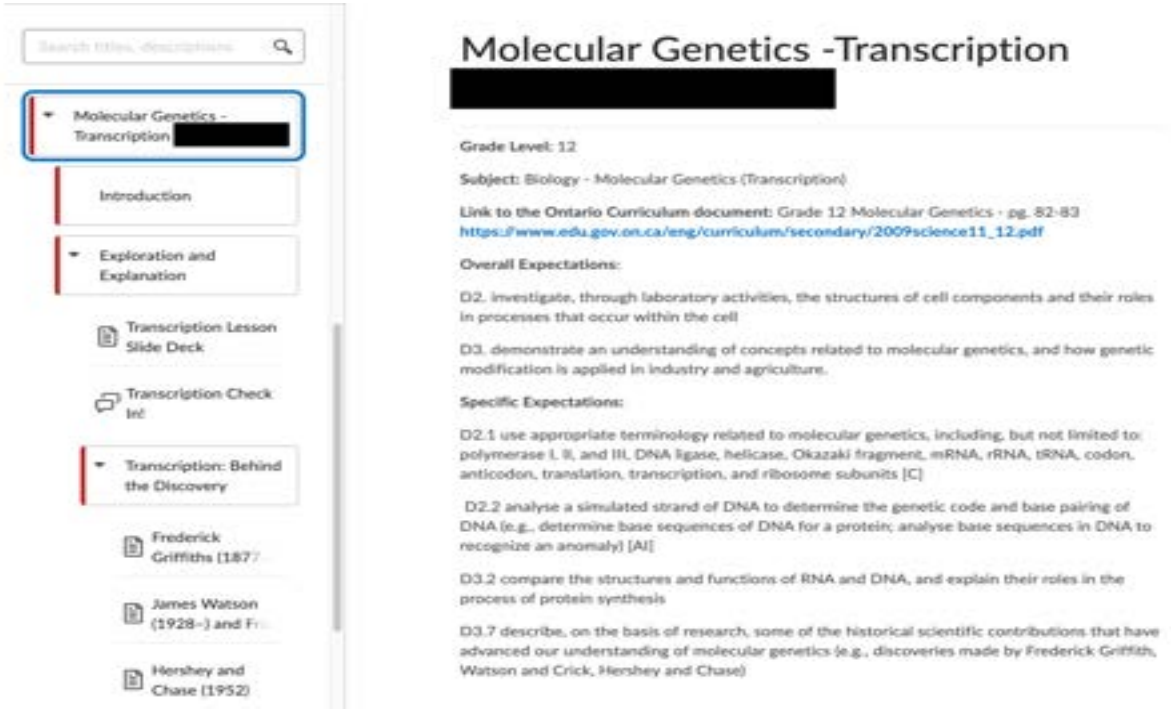
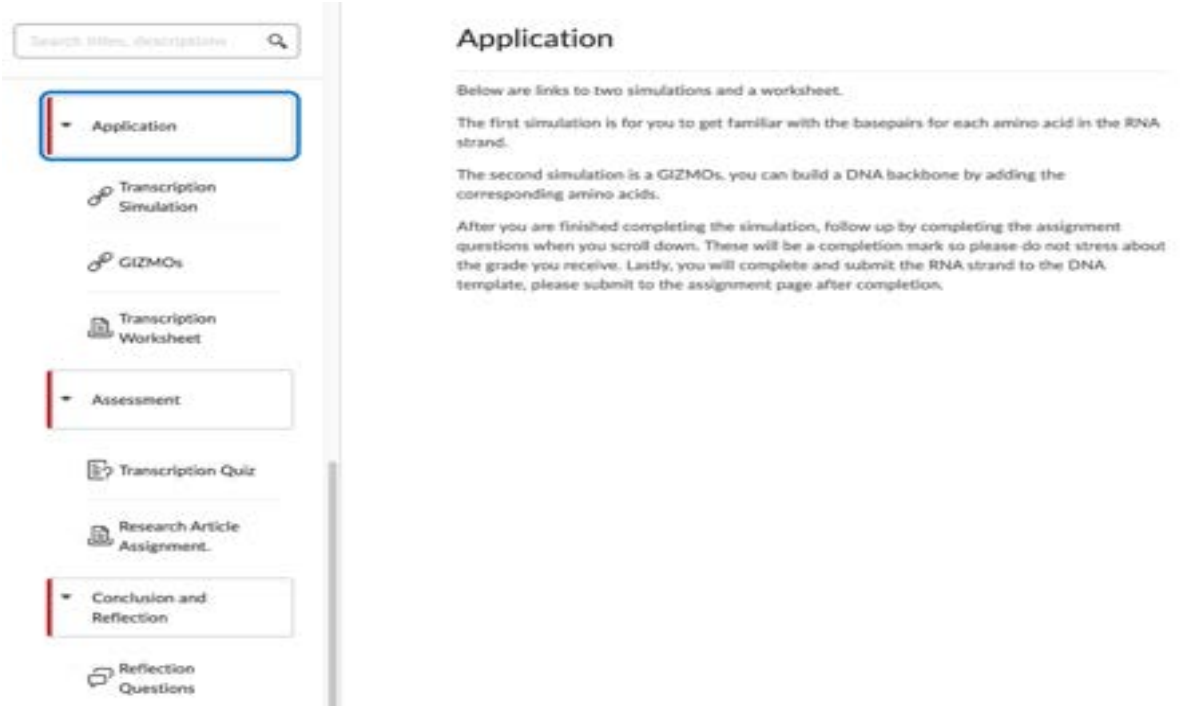


Figure 2. Screenshot of a module on DNA transcription showing the incorporation of digital tools within the module.



Teacher Candidates' Reflections

The reflections of TCs reiterated the positive impact of the training they received and the importance of the online module assignment in promoting their 1) pedagogical skills in science instructional design, 2) technological and pedagogical skills in incorporating digital tools into their lessons and using LMS. For example, TCs said:

> I think that I benefited most from finding new tech tools which can specifically be used within my teachable of science. I was able to find new virtual simulations and tutorials

which I may not have found if I did not take this course. Before taking this course, I did not consider the idea of virtual simulations, virtual field trips, and virtual labs. Having science as one of my teachables, I have realized how useful these virtual tools could be while teaching an online class and needing students to meet the lab-based curriculum expectations. I also benefited from learning how to host a class on Brightspace as this is something I will most likely need to do in the near future either during my teaching placements or within my own class.

This project gave me important insights into instructional design and online module development. Moreover, working on this subject allowed me to improve my ability to organize content effectively and create interesting learning experiences for students. In addition, I learned how to use Brightspace to host online modules, which increased my skills in using learning management systems. Overall, this project provided me with practical experience and knowledge that would be very beneficial in my future teaching career.

Significance of the Study

This research advances knowledge about science teachers' preparation and readiness for technology-enhanced and online teaching. This work informs science teacher educators, educational researchers, and higher education curriculum designers about the successes of professional development practices, especially ones focused on interdisciplinary collaborations in teacher education programs.

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Science Teacher Educators: Career Narratives And Life Histories

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A significant notion in science teacher education as in other teacher education is modelling, phrased as 'How I teach is the message'. This is both a professional and a personal stance, or stances as it spreads over several elements for the profession as a teacher educator but also makes it clear that it is the individual teacher educators personal performance applying these elements that is what teacher students meet during their education. This makes teacher education a personal effort for teacher educators and reflects the significance of teacher educators lived experiences in their teaching of coming teachers. This raise the question whether it gives different relations between work and personal life, and furthermore is science teacher educators a unique group here with distinct characteristics in their experience of meaning. My research interest calls for focus on the individual science teacher educator as it is them that do the actual teaching about science teaching. This means that I must learn from individual science teacher educators, what are their life histories, how do they narrate them during life history interviews. My analysis indicates that science teacher educators' careers are influenced by significant professional events in their lives and that second order teaching has a strong position in their professional compass.

Keywords: Science teacher educators, Career Narratives.

Introduction – Context And Background

The recruitment of teacher educators in Denmark has for the last 25 years gone through a structured qualification. This qualification is compulsory for anyone who wants to teach at a University College in Denmark including teacher educators. After 3½ years the teacher educator hands in a maximum 40 pages long written request to become a permanent member of the teacher education staff (Departmental order on teacher educator qualification, 2025). The request must cover teaching of teacher students and teachers including planning and development and implementation of international research aspects in this work. The issue of implementation of research has internationally received attention through the notion of teacher educators' varied researcherly dispositions (Tack, et al 2023). This is especially a concern for researchers from university-based teacher educations. This aspect has also been researched in Denmark (Duch et al, 2021) leading to the formulation of three idealistic types of educators at University Colleges and their relation research and development: 'The profession-oriented educator', 'The research-oriented educator', and 'The educative oriented educator'. The typologies show the spectrum of research interest among Danish university college educators but does not - as all typologies – reveal nuances and personal aspects of the research orientation. A more individualistic approach through life histories can unveil such details (Lorist & Swennen, 2016).

The structured professional development for university college educators in Denmark is not common in other countries. Studies revealed that teacher educators' recruitment is incidental, with no pre-planned policy to form well-balanced teams that provide coherent teacher education programmes (Guberman et al, 2021). It appears that Denmark holds a special position regarding a structured state-run qualification programme for a permanent position in teacher education. However, the Association of Dutch Teacher Educators run a certification programme which includes evaluation of novice teacher educators' products and portfolios (Lunenberg et al, 2014a). This certification is voluntary and does not cover all Dutch teacher educators.

A significant notion in teacher education is modelling, phrased as 'How I teach is the message' by the International Forum for Teacher Education Development (InFo-TED, 2024). This is both a professional and a personal stance, as the forum puts forward 13 building blocks for the profession as a teacher educator but also makes it clear that it is the individual teacher educators personal performance applying these building blocks that is what teacher students meets during their education. This makes teacher education a personal effort for teacher educators and reflects the significance of teacher educators lived experiences in their teaching of coming teachers (ATEE Empowering RDC, 2024).

Research Interest

A firsthand understanding of an insider – my own – is that of a great variation within science teacher educators' professional development and personal practice. The field of science teacher educators is not well researched, however there is an emerging field of international studies on being and becoming a teacher educator as well as on their lives and work (Swennen & White 2021; Jaworski & Woods, 2008; Lorist & Swennen, 2016). These studies bring forward the voices of teacher educators (Swennen & White, 2021) and critical stances to these voices (Holdsworth, 2021). As stated above the Danish qualification of teacher educators might provide a different background for the voices of Danish teacher educators. Does this give different relations between work and personal life, and furthermore is science teacher educators a unique group here with distinct characteristics in their work-life experience. This leads me to my research questions for this presentation.

Research Question

- How is science teacher educators work related to their lives?

Methodological Considerations

My stated research interest calls for focus on the individual science teacher educator as it is them that do the actual teaching about science teaching. This means that I must learn from individual science teacher educators, what are their life histories, how do they narrate them during life history interviews (White & Timmermans, 2021; Swennen & Lorist, 2016).

I can though not only interview science teacher educators. I have also to observe them during their workdays. I must contextualise my science teacher educators' narratives in the teacher educator profession and add a practice perspective on science teacher education to their narratives, so I must do more than interview them. Traianou (2007) emphasises the importance of studying actual practice:

> … the assessment of an individual's knowledge should be based on how this person performs, and not on what this person says about his/her own performance or what he/she can and cannot do in artificial situations (Traianou, 2007, p. 40).

Traianou (2007) puts her finger on the need to study science teacher educators as closely as you can get to real situations. Thus, rather than simply recounting verbatim the science teacher educators' own accounts of their practice, nor confining one's study to their performance in teaching situations, you should apply a research method that brings together diverse observational data and presents science teacher educators in all their complexity. I therefore also make observations of the participating science teacher educators teaching and performing other work functions during entire everyday work.

The Applied Method

The research design departs from the above methodological considerations which is in close alignment with a previous study on school science teachers in Denmark (Daugbjerg, 2013).

1) Life history and career narrative interview of approximately one hour
    i) Art based elements: go-cards and the like, drawing option
2) Two more-or-less whole day (each approximately 6 hours) observations pr. participants with emphasis on teaching practice.
3) Follow-up interview of approximately one hour
    i) Filling identified common aspects not covered by interview and observations
    ii) Validating preliminary interpretations of first individual interview and observations
    iii) Emotional aspects of science teacher education (e.g. joy, anxiety, nervousness)

Conceptual Framing Of The Research

Here I will briefly present research literature that presents and works with the key concepts in my research endeavour.

Second Order Teaching

Teacher educator work can be summarised in six characteristic roles of teacher educators: teacher of teachers, researcher, coach, curriculum developer, gatekeeper and broker (Lunenberg et al, 2014b). Lunenberg et al (2014b) relates in their review of teacher education these roles but especially the 'teaching of teachers' role to the notion of second order teaching. They emphasise the importance of teacher educators ability to articulate tacit knowledge and underlaying theory through explicit modelling (Lunenberg et al, 2014b).

A more recent state of the art research from Denmark puts forward a definition of second order teaching:

> Second order teaching encompasses the educative reflections concerning planning, enactment, analysis, and development of teaching, that actors in the teacher education contexts address, and the praxis they unfold to facilitate coming teachers' ability to future teaching (Ellebæk, Dolin & Daugbjerg, 2022).

Life History

Life history has frequently been used to identify significant events in peoples' lives (Goodson & Sikes, 2001). Also, within teacher education it is a known approach to understand teacher educators lives and work (Lorist & Swennen, 2016; Fisher & Powell, 2023)

Narrative Inquiry

There are several different traditions within narrative inquiry. I subscribe to a seminal work by Clandinin & Connelly (2000). Updated by Horsdal (2011):

> The focus in my approach is not to understand the individual person – how she or he really is beyond the surface – but how the narrator tries to make sense of lived experience through her narration (Horsdal, 2011, p. 108).

Narrative inquiry has also been used to understand teacher educators work e.g. White & Timmermans (2021) study on school-based teacher educators.

Findings

My participants are 8 males and 5 females, an overall cohort of Danish science teacher educators counts 62 whereof 38 are male and 24 are female (Nielsen, 2022). My group of participants is a convenience sample of volunteers, from a field that I have been a member of for nearly 30 years.

That makes my research a bit scarring because some of the participants have been my national colleagues for about a generation.

Table 1. Overview of participants biographic data.

Alias	Birth	Parents	Coming of age	Education	Career
Leif	1979	Vocational trained Ergo therapist	Rural area, scouting	Master in chemistry 2010 PhD Mol. Biophysics 2013	Science Researcher TE 2022: Physics/Chemistry
Lars	1960	Teachers	Fishing, handball	Teacher 1985, Master of education 2004	Teacher TE 2001: Biology, Nature/Tech
Nete	1980	Vocational trained Nurse	Sports	Teacher 2006 Master of SE 2022	Teacher TE 2022: Physics/Chemistry
Niels	1985	Farming	Choir, outdoor life	Music studies Master of Geography 2009	High school teacher TE 2018: Geography
Alex	1961	Unskilled	Music,	Teacher 1990 Master of education 2000	Teacher TE 2009: Physics/Chemistry
Anders	1955	Own shop	Scouting, running	Teacher 1978 Master of education 2000	Teacher and consultant TE 2003: Nature/Tech, Further education
Veronika	1972	Teachers	Gymnastics, scouting	Biologist 2000 PhD zoology 2003	Science Researcher TE 2009: Biology
Viola	1965	Teachers, artists	Drama, scouting, sports	Biologist 1990 PhD outdoor pedagogy 2020	High school and TE 1993: Biology
Villiam	1953	Teachers	India, music	Teacher 1985 Master of education ????	Teacher, social worker TE 2002: Biology, Nature/Tech
Sanne	1972	Farming, teachers	Sports, Arts	Theology Teacher 2000, ME 2013	Teacher, consultant TE 2016: Biology
Steen	1966	Semiskilled	Sports	Physics and math 1993	High school and TE 1996: Physics/Chemistry, Math
Kia	1983	Farming	Scouting	Geology 2009 PhD meteorites 2014	Science centre TE 2016: Nat/Tech, Geography
Karl	1970	Welfare professionals	Sports including chess	Geography and history 2001	Teacher TE 2004: Geography, Further education

They represent a geographical distribution in Denmark with participants from all 6 university colleges in Denmark, they represent all the four science subjects in Danish school and teacher education. Biographic data that present the overall life histories are presented in the table below. Interviews and observations were conducted from November 2023 – February 2025.

Comparison of my participants with the overall cohort of Danish Science teacher educators reveals that my sample quite representative for science teacher educators in Denmark in general.

Table 2. Comparison of my participants experience as science teacher educator and a larger cohort of Danish Science teacher educators.

Experience as Science teacher educator	National cohort (N=57) (Nielsen, 2022)	My participants (N=13)
0-4 years	21%	15%
5-9 years	16%	23%
10-14 years	9%	0%
15-19 years	23%	23%
20 years or above	32%	38%

Table 3 Comparison of my participants educational background and a larger cohort of Danish Science teacher educators – several has more than one education e.g. a teacher education and a Master of Science Education or a Master of Science and a PhD degree.

Science teacher educators educational background	National cohort (N=57) (Nielsen, 2022)	My participants (N=13)
Teacher education	36%	46%
Science master	62%	54%
Science education Master	22%	38%
Other master	31%	0%
PhD	31%	31%
Other education	33%	15%

Voices Of Science Teacher Educators

My participants reflect the importance of second order teaching as a way to be a teacher of teachers:

> And then the challenge with second order teaching. That is what I find most interesting (Kia).

Kia has worked with young children at a science centre prior to entering teacher education, here she applied a variety of teaching approaches. These experiences are mirrored in her approach working with science modelling with her science teacher students as a tool to relate to them and make them relate to science.

> And then I work simply with [modelling], rather than sitting and getting frustrated that they can't understand it [the science subject as presented in a text]; I say, that is okay that you do like this [make a model] (Kia).

Kia asks the science teacher students to work with a science phenomenon through different media as they see fit to optimize their learning.

My participants also reflect on specific elements of science education and the duality of teaching and learning.

> Science, aesthetics, and the fascination. Evolution as the red thread and the connection between learning and teaching (Veronika).

Veronika also reflects on the relation between science education research and science teacher education and its options for double synergies. Veronika has been a science researcher prior to entering teacher education.

> Because I research into teaching, and that must be anchored. So, I anchor it in my own [teacher education] praxis. I try to include it [research] and try to use the synergies (Veronika).

My participants also refer to significant events in their career

> I had these two supervisors … who also were Danish language teachers. They had a lot of focus on language … and then ever since I have had a lot of focus on language in science and mathematics (Sten).

Sten also narrates another significant event from a stay abroad, where he met a science supervisor who encouraged him to work extensively with practical work in the science lab. He recalls the instruction he was given:

> '*When you think you have investigated it sufficiently, then you make a report and then you take the next'*. So, there was much more freedom. And there were much in the teaching that dealt with experimental methods, contrary to what I was used to back at University in Denmark (Sten).

Stens work with coming physics teachers is based on a lot of practical experimental work in the science lab, so Sten has implemented his own experience with lab work in his praxis. He emphasizes the importance of his science teacher students to be comfortable working with experiments themselves and together with students in school.

Some of my participants work with in-service training of school science teachers and how their former career as a school science teacher eases them in their role as a broker for school science teachers in their professional development.

> Well, I love to do continuous education for teachers, but that is also because I have been doing it for so many years. And I have been a colleague with them. I can see that some of the new young ones [science teacher educator colleagues] that come the university way, they hurt themselves on them [school teachers]. Really schoolteachers are the most critical race you can teach, but that is because they sit in it [teaching] daily themselves (Lars).

Table 4. Summary of how work and life relate in science teacher educator roles seen in my participants career narratives.

Teacher of teachers	Broker	Researcher
Commitment in the relation to teacher students using own teacher experience.	Relation to teachers - Own experience as a teacher.	Experience with research: - Prior to entering teacher education

Focus on making science teacher students comfortable with doing practical experimental work with school students based on own experience with science lab work.		- As a part of being a teacher educator

Conclusion

The presented voices indicate that science teacher educators' careers are influenced by significant professional events in their lives and that second order teaching has a strong position in their professional compass. There are general teacher educator aspects in the narratives e.g. relating to teacher students and schoolteachers, but there are also references to science education elements such as science modelling or experimental work and grand narratives of science like evolution as a red thread.

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Examining Pre-Service Chemistry Teachers' Perceptions About Their Interactions With Mentors And Peers During The COVID-19 Pandemic

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This study explores the pre-service chemistry teachers' perception of mentoring relationships within the context of the Brazilian Pedagogical Residency Program (PRP), focusing particularly on the challenges posed by the COVID-19 pandemic and the shift to remote learning. The PRP, a public policy designed to enhance teacher training, pairs pre-service teachers with experienced in-service mentors and fosters peer mentoring to develop practical teaching skills. This study investigates how these mentoring relationships contributed to the development of pre-service teachers' teaching practices, especially considering challenges posed by the pandemic. Two key research questions were addressed: the role of in-service mentors and peers in shaping teaching practices, and how the pandemic affected these mentoring relationships. Data were collected through interviews, experience reports, and audiovisual recordings from six pre-service teachers who participated in the PRP between 2020 and 2022. The findings emphasize the essential role of in-service mentors in providing guidance; however, communication barriers were enhanced by the remote learning context. Although peer mentoring emerged as a valuable source of emotional and professional support, the physical absence of mentors led to more superficial mentor-mentee interactions. The study underscores the importance of strong communication and deeper engagement in mentoring relationships, particularly during times of crisis. It also suggests that future improvements in mentoring training and program design could enhance the effectiveness of teacher training programs. The research contributes to understanding how mentoring dynamics influence pre-service teacher development and provides insights for refining educational policies in Brazil and beyond.

Keywords: Pre-service teacher education, Professional development, Educational Policy

Introduction

Mentoring is discussed in the literature from different perspectives. More traditional and classical views of mentoring consider it as a process where knowledge is transferred from the mentor to the mentee in a more hierarchical manner (Spooner-Lane, 2017). In contrast, more modern views emphasize a collaborative and mutually beneficial approach to educational mentoring (Larsen et al., 2023).

Regardless of which perspective researchers align with, they consistently highlight the importance of the relationship between mentors and mentees in the mentoring process. In this context, Brazil has recently implemented public policies that describe mentoring programs for pre-service teachers, such as the Brazilian Pedagogical Residency Program (PRP). Science pre-service teachers have been a primary focus of educational policies, particularly due to alarming university dropout rates. Research attributes this high rate the absence of active and interdisciplinary teaching and learning strategies (Silva & Figueiredo, 2018).

Additionally, pre-service teachers in Brazil have a highly demand coursework that requires them to take pedagogical core courses while also taking content-specific pedagogical courses and content-specific courses, contributing to these rates. Previous studies indicate that challenges in mathematics-related coursework may contribute to science pre-service teachers drop-out rates (Heusel et al., 2023). With that said, it is important to have a deep understanding of how these

new policies, focused on mentoring programs, are influencing student-teachers to persist in and complete their degrees.

Since the onset of the COVID-19 pandemic in 2020, much has been discussed about its impact on fields such as education and pre-service teacher training. However, little is known about how it may have hindered mentoring programs like PRP. This investigation draws on data from this period, which adds uniqueness and importance to understanding whether and to what extent the pandemic may have affected pre-service teachers' experiences in a mentoring program.

This study aims to identify aspects of the relationship between mentors (in-service teachers) and mentees (pre-service teachers) that may have provided support to the mentees as they began their teaching practices, according to their perspectives. Two research questions are posed:

RQ1: According to pre-service chemistry teachers' perceptions, what role did in-service teacher mentors and peers play in helping them develop better teacher practices?

RQ2: According to pre-service chemistry teachers' perceptions, how did the pandemic and the remote learning context hinder their relationships with peers and in-service teacher mentors?

Framing

Teacher Perception

In Science Education literature, studies frequently draw on teachers' and students' perceptions to analyse experiences, practices, and learning environments. However, despite its widespread use, the concept of perception is often taken for granted and remains theoretically underdefined. In this study, perception is understood not as a passive registration of events, but as an active cognitive process through which individuals interpret, organize, and attribute meaning to their experiences.

From a cognitive perspective, perception is grounded in prior experiences and embodied interactions with the world. According to Kiefer and Trumpp (2012), perception and cognition are inseparable, as cognitive processes are rooted in sensorimotor experiences accumulated over time. This embodied view suggests that individuals do not merely perceive situations as they are, but rather reconstruct them based on previous experiences, actions, emotions, and contextual cues. Thus, what pre-service teachers perceive in mentoring relationships is shaped by their trajectories, expectations, and the specific conditions under which those interactions occur.

Goldstone et al. (2010) further argue that perception is not limited to what is immediately visible or apparent. Instead, perception is educable and adaptable, evolving as individuals learn to attend to features of situations while ignoring others. In educational contexts, this means that learners and teachers develop perceptual frameworks that guide how they interpret complex environments, such as classrooms, professional relationships, or collaborative practices.

Importantly, this perspective challenges the idea that perception is superficial or opposed to deeper understanding. As Goldstone et al. (2010) demonstrate, perceptual processes can be aligned with conceptual reasoning, allowing individuals to make sense of abstract or complex phenomena through learned interpretive lenses. In teacher education, this implies that pre-service teachers' perceptions of mentoring and peer interactions are not merely subjective impressions, but meaningful constructions that reflect how they make sense of professional learning experiences.

Literature Review

Mentoring Relationships

As previously stated, mentoring relationships are extremely important to determine the efficacy of a mentoring program. In science teacher education, these relationships are even more important, because teachers need to envision classrooms as communities of practice. Teachers need to envision science classrooms that engage students with learning science as communities. Mentor-mentee effective relationships can help pre-service teachers to develop the skills they need to build such classroom environments (Abed & Abd-El-Khalick, 2015).

The literature on mentoring in teacher education presents both traditional and contemporary perspectives that reflect different assumptions about learning, professional development, and the roles of mentors and mentees. More traditional views conceptualize mentoring as a hierarchical process in which knowledge, norms, and practices are transmitted from a more experienced teacher to a novice in a largely unidirectional manner (Spooner-Lane, 2017). In this model, the mentor is positioned as an expert whose primary role is to guide, evaluate, and support the mentee's adaptation to the profession.

In contrast, more recent approaches frame mentoring as a collaborative and mutually beneficial process, emphasizing dialogue, shared reflection, and co-construction of professional knowledge (Larsen et al., 2023). From this perspective, mentoring is understood as a relational practice in which both mentors and mentees actively negotiate meanings, roles, and expectations. Rather than focusing solely on transmission of established practices, contemporary mentoring models highlight reciprocity, trust, and professional learning for all participants involved.

Despite differences in conceptualization, researches indicates that mentored teaching practice can be a powerful component of initial teacher education. Studies have shown that mentoring by experienced teachers can support pre-service teachers in developing pedagogical skills, professional confidence, and a sense of belonging to the teaching profession (Spooner-Lane, 2017). However, the literature also cautions that mentoring is not inherently beneficial. Ineffective mentoring relationships, characterized by poor communication, limited feedback, or misaligned expectations, can negatively impact teacher development and, in some cases, be more detrimental than the absence of mentoring altogether (Tuma et al., 2021).

Effective communication emerges as a central element in productive mentor–mentee relationships. Roehrig et al. (2008) emphasize that frequent and meaningful interactions between mentors and mentees enable pre-service teachers to reflect on practice, receive targeted feedback, and emulate effective teaching strategies. Communication that is dialogic rather than prescriptive allows mentees to engage more deeply with their professional learning and to critically examine their instructional choices.

In the context of science teacher education, mentoring relationships assume particular importance. Preparing science teachers involves more than developing general pedagogical skills; it requires helping future teachers envision science classrooms as communities of practice in which students actively engage in inquiry, modelling, argumentation, and collaborative knowledge construction. Abed and Abd-El-Khalick (2015) argue that effective mentoring can support pre-service science teachers in developing the pedagogical and epistemic skills necessary to foster such classroom environments. Through observation, modelling, and reflective dialogue, mentors can help mentees align their teaching practices with contemporary goals of science education.

COVID-19 And Science Teacher Education

The COVID-19 pandemic profoundly disrupted science teacher education worldwide, challenging established assumptions about teaching, learning, and mentoring. Central to these challenges was the difficulty of enacting science-as-practice approaches, widely emphasized in contemporary science curricula, which rely on classroom interaction, inquiry, collaboration, and situated engagement with scientific practices. In remote and hybrid learning contexts, ensuring meaningful engagement with science practices became particularly challenging for both in-service and pre-service teachers (Haidusek-Niazy et al., 2023).

Scholars have raised critical questions about whether online and remote experiences can effectively support the development of pre-service science teachers' capacity to enact core instructional practices. Campbell et al. (2021) argue that practice-based approaches to science teacher education, such as rehearsals, approximations of practice, and clinical experiences, were significantly constrained during the pandemic. The abrupt shift to remote instruction limited opportunities for pre-service teachers to engage in authentic classroom environments and to interact with students in ways aligned with inquiry-oriented and justice-informed science teaching.

In Brazil, the pandemic had a particularly strong impact on pre-service teachers enrolled in programs that relied on school-based experiences. Student teachers who were expected to be physically present in schools were suddenly removed from classroom contexts, restricting their opportunities to familiarize themselves with school routines, student interactions, and the social dynamics of teaching. As a result, mentoring relationships, traditionally grounded in shared physical spaces and *in situ* observation, were reshaped by the hinderances of remote interaction.

At the same time, the pandemic context gave rise to new forms of mentoring and professional support. Haidusek-Niazy et al. (2023) document the emergence of peer mentoring and reverse mentoring practices during the COVID-19 crisis, particularly in technologically mediated environments. In many cases, pre-service and early-career teachers supported more experienced mentors in navigating digital tools and online teaching platforms, temporarily reversing traditional hierarchical roles. Additionally, peer mentoring among teachers became a critical source of emotional, pedagogical, and technological support, often compensating for weakened or disrupted formal mentoring structures.

Understanding pre-service teachers' perceptions of mentoring and peer interactions during this period is therefore essential for capturing how science teacher education was reconfigured under pandemic conditions. By examining these perceptions, this study contributes to ongoing discussions about the possibilities and limitations of mentoring in times of crisis and offers insights into how alternative mentoring arrangements may inform future models of science teacher education.

Methodology

The Brazilian Pedagogical Residency Program (PRP) is a public policy in Brazil aimed at enhancing pre-service teacher training by immersing participants in the teaching routine during the final three semesters of their undergraduate studies, as part of their student teaching. Participants collaborate with experienced in-service teacher mentors at designated schools, engaging in tasks such as observations, lesson planning, and reflective practice. A unique feature of the PRP is its emphasis on collaboration, where pre-service teachers also act as peer mentors,

discussing and criticizing each other's lesson plans to foster critical reflection and practical skill development.

This study involved six pre-service chemistry teachers with no prior teaching experience who participated in the PRP between 2020 and 2022. Part of the program took place during the COVID-19 pandemic, when activities were conducted through emergency remote learning. This context required a nuanced analysis, as mentoring relationships and teaching practices were shaped by the constraints of remote interaction.

Data were collected through audiovisual recordings, written experience reports, and semi-structured interviews. All ethical procedures were followed, including the signing of informed consent forms granting permission for data use. To ensure anonymity, participants' names were replaced with pseudonyms throughout the analysis.

The data were coded focusing on pre-service teachers' perceptions of their relationships with mentors and peers (Saldaña, 2025). Coding was conducted inductively, allowing categories to emerge from the data in alignment with the research questions. This process supported an in-depth examination of how participants interpreted their mentoring experiences.

From this, we looked for themes that described the codes through thematic analysis (Clark & Braun, 2017). Initial coding was conducted individually, with categories refined through iterative revisions of the dataset. Two researchers independently analysed the data and subsequently discussed the findings to reach consensus, ensuring rigor, reliability, and validity in the qualitative analysis (Kuckartz, 2014).

From this process, three main themes emerged: (i) Navigating Support in Relationships with In-Service Mentors; (ii) COVID-19 Enhanced Challenges; and (iii) Peer Mentoring as a "Safe Space".

Findings And Discussion

Navigating Support In Relationships With In-Service Mentors

Pre-service teachers recognized the value of in-service mentors, particularly for lesson planning and for understanding the constraints and possibilities of the school context. Mendeleev emphasizes that mentors' classroom experience and familiarity with school routines were crucial for planning intervention activities. This support helped pre-service teachers situate their proposals within the realities of the school environment.

In addition to practical guidance, mentors were perceived as open and supportive in their interactions. According to Oppenheimer, "I always felt that the preceptors were present and interested, and were willing to help, you know?!" (Oppenheimer, Interview 1). At the same time, the pre-service teacher highlights that this support was accompanied by freedom to innovate, as mentors encouraged discussion and autonomy in planning activities: "[...] they [in-service teachers] were willing to discuss, I felt this freedom for us to come up with whatever we wanted" (Oppenheimer, Interview 1).

Together, these perceptions suggest that mentors played an important role by balancing guidance with autonomy. Even within a remote or hybrid context, pre-service teachers valued mentors' contributions to planning and decision-making, particularly when these interactions allowed space for dialogue and creative pedagogical choices.

COVID-19 Enhanced Challenges

Despite recognizing the importance of mentors, pre-service teachers pointed out two main concerns that hindered their experience in the PRP: communication and superficiality in

relationships. Communication issues were especially evident in the early stages of the program, when the teachers were often absent from weekly group meetings. According to the participants, this absence negatively affected coordination and planning processes.

Oppenheimer recalls a specific situation in which communication failures directly impacted the development of activities: “I remember one of the preceptors did not respond to one of my colleagues, I don't remember who it was. The person sent him an audio message, and he never listened to it, so there was a communication failure in the planning” (Oppenheimer, Interview 1). Such episodes reinforced the perception that maintaining open communication channels was particularly challenging during remote interactions.

In addition to communication barriers, pre-service teachers described their relationships with mentors as superficial. Enrico explains that his contact with the teachers was largely restricted to PRP-related activities, which limited deeper interaction and integration. He acknowledges that failures occurred on both sides, particularly regarding communication, which contributed to this sense of distance.

This superficiality, however, does not appear to be identified as the core problem, but rather because of communication challenges and contextual constraints. Marie reflects on the organization of the subproject’s weekly meetings, noting that greater participation from the teachers could have strengthened relationships with the undergraduates. Pre-service teachers also demonstrated understanding of the broader context, recognizing that the pandemic and emergency remote teaching likely reduced in-service teachers’ availability. As Enrico reflects, “I don't think I pursued enough, and I say this also because I already thought the teachers were too overwhelmed with the pandemic” (Enrico, Interview 1).

Marie further elaborates on these challenges in her supervised internship report, acknowledging that access to mentor teachers was compromised by remote and hybrid teaching conditions. However, she suggests that the issue extended beyond availability alone: “The remote teaching thing is really bad. [...] I had no direction, but so did the teachers, because the Department of Education wanted something every time” (Marie, Report).

Previous studies indicate that mentoring by experienced teachers can be a valuable component of initial teacher education (Can-Kucuk et al., 2022), while ineffective mentoring can hinder mentees’ experiences (Tuma et al., 2021). In line with these findings, the results of this study reveal how disrupted communication and limited interaction constrained mentoring relationships during the pandemic. Even so, pre-service teachers continued to recognize the importance of mentors, while acknowledging that the lack of physical presence and sustained interaction hindered the development of deeper professional relationships.

Peer Mentoring As A “Safe Space”

In contrast to the challenges experienced with in-service mentors, pre-service teachers consistently described peer interactions as supportive and meaningful. Boyle highlights the contribution of peers to lesson planning during weekly meetings, which he viewed as particularly positive. According to him, collaborative planning enabled exposure to different perspectives and enriched decision-making: “planning a group teaching sequence was interesting, because the conversation between the three of us [pre-service teachers] during the process of preparing the classes allowed for contrasting views on the same subject in favor of student learning” (Boyle, Report).

Peer meetings were also described as safe spaces for discussion and reflection. Mendeleev explains that videoconferences with other participants in the subproject felt comfortable because

the group members were already familiar with one another. This sense of familiarity fostered openness and trust, encouraging participants to share ideas and concerns freely.

Marie reinforces this perception, emphasizing the collaborative nature of peer discussions: “We [pre-service teachers] brought the ideas we had, the other colleagues discussed them, I thought it was really good, really positive” (Marie, Interview 1). The longevity of their relationships and shared experiences within the program contributed to a sense of safety that supported reflection and mutual learning.

These findings align with previous research suggesting that informal mentors, such as peers, can provide important emotional and professional support during teacher preparation (Desimone et al., 2014). While in-service teachers offered practical knowledge about school contexts and constraints, peers played a complementary role by creating spaces for dialogue, emotional support, and collaborative sense-making. Together, these different forms of mentoring contributed to pre-service teachers’ professional learning during a particularly challenging period.

The findings of this study highlight the importance of informal mentoring, particularly among peers, as participants reported feeling safe to express their opinions about lesson plans and teaching activities developed by others. This sense of safety appears to be central to peer mentoring interactions, enabling open dialogue, critical reflection, and mutual support during the planning process. The idea of a safe space for discussing pedagogical ideas is not limited to peer mentoring but is fundamental to mentoring relationships more broadly, as previously emphasized by Luft et al. (2022).

Although the emergence of peer and reverse mentoring during the COVID-19 pandemic has been discussed in the literature (Haidusek-Niazy et al., 2023), these forms of mentoring have been primarily examined among in-service teachers. The findings of the present study extend this discussion by showing that peer mentoring also played a central role among pre-service teachers, functioning as a critical source of pedagogical and emotional support during emergency remote teaching.

These results also reaffirm that teachers’ autonomy was significantly constrained during the pandemic by institutional, technological, and regulatory demands (Campbell et al., 2021). In this context, older educators, who traditionally served as mentors, were often overwhelmed by the need to adapt to new technologies, limiting their capacity to provide sustained support to novice teachers (Kraft et al., 2020). As a result, peer mentoring among pre-service teachers emerged not only as complementary practice but as a necessary space for professional learning and sense-making in a period of crisis.

Conclusions

Overall, the pre-service teachers recognized the value of both in-service mentors and peers in their professional development. Mentors contributed primarily through professional guidance, offering feedback on lesson planning and classroom activities that supported reflection on pedagogical practices. These interactions helped pre-service teachers identify strengths and areas for improvement, reinforcing the importance of experienced teachers in initial teacher education.

This appreciation underscores the role of mentoring programs such as the Brazilian Pedagogical Residency Program (PRP) in strengthening the connection between universities and schools. By immersing pre-service teachers in school contexts, the PRP provides opportunities for situated learning, collaborative reflection, and engagement with the realities of teaching. At the same time,

the findings suggest that mentoring relationships are central to how pre-service teachers make sense of these experiences and adjust their practices.

The COVID-19 pandemic, however, significantly reshaped mentoring dynamics within the program. Communication difficulties and limited interaction hindered the development of deeper mentor–mentee relationships, often resulting in more superficial exchanges. These challenges were largely attributed to emergency remote teaching conditions, institutional demands, and the overload experienced by in-service teachers during the pandemic.

Despite these constraints, peer mentoring emerged as a strong and consistent source of support. Pre-service teachers described peer interactions as safe spaces for sharing ideas, expressing concerns, and collaboratively reflecting on teaching practices. Even in a context marked by uncertainty and disruption, peer relationships helped sustain professional learning and emotional support, highlighting the relevance of informal mentoring structures in teacher education.

Taken together, these findings point to the need for future research and program design to place greater emphasis on mentoring skills, particularly communication and expectation-setting. Further studies should expand the scope of analysis to explore the broader mentoring context in teacher education programs and investigate how peer mentoring can be intentionally fostered among pre-service teachers. Strengthening mentoring practices, both formal and informal, may enhance the quality of science teacher education and contribute to the long-term success of public policies such as the PRP.

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Physics as Culture: Dialogues for a Critical and Sustainable Teacher Education

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The progress toward a sustainable society, focused on building a viable and equitable future, has become a key issue on the international stage. According to research in the field, tackling this difficulty requires a focus on culture as well as the development of critical, reflective educators. In the context of physics teacher preparation, it is critical that potential educators get an in-depth comprehension of physics as both, a scientific subject and a cultural construct. This study sought to investigate the fundamental components involved in the foundational training of physics educators, with the goal of suggesting methods that promote sustainable scientific education rooted in the recognition of physics as a vital part of culture. We examined the discourses of undergraduate physics students, gathered through a questionnaire, to accomplish this. The analysis was conducted using Pêcheux's Discourse Analysis, with the assistance of theoretical frameworks in physics pedagogy and teacher education. The attendees mainly view physics to elucidate natural occurrences, largely overlooking the historical, social, ideological, and philosophical dimensions that shape the discipline. This viewpoint highlights an absence of thoughtful consideration among upcoming educators. The arrangement of the undergraduate curriculum, frequently divided into distinct sections, could play a role in these patterns, and impede the cultivation of critical thinking skills. As a result, the research emphasizes the necessity of developing curricular strategies in the early training of physics educators that foster critical, transformative, and sustainable scientific education.

Keywords: Physics as culture, sustainable development, teacher training.

Introduction

The development of a sustainable society, committed to constructing a feasible and equitable future, has emerged as one of the foremost global imperatives. Inspired by the need to tackle complex sustainability issues spanning economic, social, environmental, and ethical domains, the United Nations (UN) drafted a landmark report titled "The 2030 Agenda for Sustainable Development" (UN, 2015).

In this sense, the exploration of culture's influence in promoting an engaged, sustainability-focused community has garnered significant academic attention and discussion. Viesba-Garcia et al. (2019) argue that sustainability education helps society move from its existing state to a more desired reality based on sustainable principles. Culture emerges as a critical component in this process, given its essential function in facilitating societal adaptability, stimulating the production of new knowledge, and consolidating values and traditions aligned with sustainability. Thus, achieving sustainable development is deeply connected to the cultural evolution and appreciation of communities—a process facilitated through education.

The initial education of physics teachers, grounded in the principles of cultural integration and sustainable development, is predicated upon the practice of critical reflection. Freire (2020) asserts that critical reflection enables educators to engage in a deeply meaningful process of professional self-recognition, which is actualized through the integration of cultural elements. When looking at how to train physics teachers using critical reflection as a framework, Nardi & Castiblanco (2018) emphasize that the teaching of Physics Didactics must develop methodologies capable of addressing content in ways that cultivate undergraduates' critical thinking skills, thereby empowering them to construct independent understandings of teaching practices. Lima

& Bozelli (2024) further argue that critical reflection positions teachers as intellectual agents who fulfill a vital social role by creating, promoting, and disseminating cultural knowledge.

Given these considerations, the present study seeks to investigate key aspects of the initial education of physics teachers, with the aim of delineating strategies conducive to a sustainable scientific education framework that is deeply rooted in the conceptualization of physics as culture.

Physics As Culture In The Education Of Critical Intellectual Teachers

One of the pioneers in Brazil to explore the importance of critical reflection in teacher education was the educator Paulo Freire. In several of his works (Freire, 2019; 2020), he expressed that the transformation of the contemporary world occurs through the critical reflection and action of men and women upon the world. In dialogue with these perspectives, Giroux (1997) argues that educational practice grounded in critical reflection provides educators with greater autonomy, in favor of an education rooted in the struggle for the transformation of social reality, aiming to overcome economic, social, and political injustices. Contreras (2002), in turn, when considering a model of teacher education grounded in critical reflection, conceives the teacher as a transformative intellectual, whose pedagogical action is intrinsically connected to the promotion of social equity through the construction of a more democratic and sustainable society.

Thus, in deliberations regarding the inclusion of Physics as culture in the education of critically reflective teachers, the imperative emerges to conceive a Physics teaching process that incorporates a dynamic and active scientific culture, in accordance with the Freirean perspective, that is, one that seeks the transformation of the contemporary world toward a sustainable world. As observed by Zanetic (1990), this purpose implies consideration of certain conditions, including: (1) the improvement of teaching and learning processes so that students become capable of solving theoretical problems both in Physics and in everyday life; (2) the deconstruction of the veneration of the traditional scientific method that currently prevails; (3) the conceptualization of Physics as a component of social history, that is, Physics as it developed alongside historical events; and (5) the presentation of contemporary Physics and the explicit discussion of its relevance in the contemporary global context, since only through this approach is it possible to foster the perception of Physics as a cultural element.

In this context, the need emerges to attribute significance to the development of Physics and to its capacity to influence social transformation. Zanetic (1990) expresses concern regarding the economic, political, religious, and cultural aspects that make up the History of Physics. This is especially relevant, since, about culture, Science, particularly Physics, often remains invisible. From this perspective, culture is frequently restricted to literary works and artistic expressions such as painting, dance, and music, a direct consequence of the educational system, which does not contemplate the teaching of science as culture and thus contributes to alienating Physics from people’s everyday lived experience.

The deficiency in the development of a scientific culture is not a problem restricted to Brazil, but rather a reality observable in several countries, due to the promotion of a culture that becomes disconnected from reality. The connection between science and economic and social foundations is of great importance for understanding its role in the cultural context. It is through this interrelation that the construction of a Physics education that is both critical and pragmatic becomes possible.

For Zanetic (1990), the conception of Physics as culture requires the inclusion of externalist components, namely: influences of a socioeconomic nature, ideological approaches, formulations of scientific methods, the dynamic history of Physics, experimentation, scientific theories, and their practical applications. The integration of these elements is fundamental to confer concrete

relevance to Physics in the education of citizens. Another important aspect in considering Physics as a cultural component is interdisciplinarity, as it enables the integration of Physics with other fields of knowledge and with the world more broadly. Thus, as discussed by Nardi and Castiblanco (2018), it becomes necessary for teachers of this discipline to draw on other forms of knowledge beyond the specific Physics content learned at university, incorporating externalist components into their teaching practices.

Theoretical And Methodological Foundation

The foundation of this study's theoretical and methodological framework is rooted in Pêcheux's Discourse Analysis (DA), as described by Orlandi (2015), and is further enriched by insights from a theory of teacher education with a critical stance, as outlined by Freire (2020). Additionally, we integrated contributions from the physics education domain, drawing on the works of Nardi & Castiblanco (2018) and Zanetic (1990).

We collected the research data by administering a questionnaire with ten open-ended essay questions in a didactic-pedagogical course to final-year students enrolled in a physics degree program at a Brazilian public university. The data analysis was carried out by developing an analytical framework based on the theoretical and methodological principles discussed thus far. As highlighted by Orlandi (2015), the construction of an analytical framework enables the researcher to navigate the boundaries of interpretation and to delineate the research object with precision.

A total of 14 undergraduate students enrolled in the course participated in the study. Owing to space constraints, this research selected the discourses of four participants for dissemination. The selection was based on the representativeness of their responses in relation to the broader group of participants.

The principles of Discourse Analysis (DA) guided the construction of the corpus for analysis, aligning it with the objectives of this research. Orlandi (2015) emphasizes that theoretical, not empirical, criteria determine the selection of the corpus. This approach reflects the foundational premise of DA, which does not aim to encompass all empirical elements associated with the object of study but rather focuses on those elements that align with the specific analytical objectives at hand.

Discourse Analysis Of The Undergraduate Students

We developed two collaborative gatherings in this context. The first one sought to examine undergraduate students' understanding of the concept of physics, employing the following question as a point of departure: "How would you explain to a high school student what physics is?" Table 1 systematically organizes the responses provided by the undergraduate participants.

Table 1. Undergraduates (with fictitious names) give speeches about physics

NAMES	GRADUATES' RESPONSES TO THE QUESTION
Gisele	I would explain that physics is the ability to explain why "things" move.
Luana	I would explain that physics is a natural science that aids in our understanding of the world around us.
Marcos	Physics is a way of experiencing things.
Mario	I would explain that physics is the science that explains how the universe works based on energy transformations.

Undergraduate students' writings show that they think of physics mainly in terms of how it explains natural events, with its historical, philosophical, ideological, and social aspects being less important. This comprehension is intrinsically linked to the imaginative formations of physics and scientific knowledge that undergraduate students have developed because of their production experiences. Most students point to their initial exposure to physics during high school as predominantly instrumental, emphasizing the resolution of mathematical exercises and the memorization of concepts.

These findings are consistent with existing literature in the field. Undergraduates, according to Nardi and Castiblanco (2018), tend to look back on their high school experiences when reflecting on their basic education, particularly in cases when critical reflection is not effectively addressed in teacher preparation programs. Zanetic (1990) further highlights that the dissociation of Physics from its cultural dimensions can be attributed to the way the subject is taught in high schools. This teaching approach is typically focused on the "teaching/learning" process of solving exercises and problems, with limited attention given to experimentation, theoretical analysis, and the exploration of the historical and conceptual development of Physics as a field of knowledge.

Moreover, the discourses produced by undergraduate students reveal a noticeable gap in their engagement with an educational-critical approach, as these discourses fail to incorporate the historical, social, and political elements that influence the construction of scientific knowledge.

Building upon these considerations, we designed the second collaborative gathering to explore in greater depth how undergraduate students conceptualize the relationship between physics and culture. To this end, we presented the following question: "In your opinion, what is the relationship between Physics and culture? Please explain." Table 2 below systematically organizes the responses provided by the undergraduate students.

Table 2. Speeches by undergraduates (fictitious names) about physics as a culture

NAMES	GRADUATES' RESPONSES TO THE QUESTION
Gisele	I believe that every area of knowledge is a form of culture. This includes physics.
Luana	I believe that Physics is culture, as it is part of the knowledge produced by civilizations historically.
Marcos	In the same way that science and society are collaborative with each other, Physics and culture are too.
Mario	Physics explains sound and music… It explains the climate that governed the establishment of peoples in different regions, transforming customs and cultures.

Examining the discursive outputs of undergraduate students shows that they express their ideas through unique imaginary constructs, which can be generally categorized into two projection types. The initial category, as expressed by the perspectives of all undergraduate students aside from Gisele and Luana, perceives physics and culture as distinct realms, where one either influences or enhances the other. The second category, as articulated by Gisele and Luana, views physics as a manifestation of culture—an inseparable and inherent phenomenon It is necessary to acknowledge that physics reflects society to conceptualize it as culture. According to Zanetic (1990), the knowledge we acquire in science emerges from social interactions and reflects the cultural context in which it is developed. Scientific knowledge is an integral component of this culture, and it is both influenced by other fields of knowledge. Therefore, perceiving physics as culture implies recognizing it as a product of social dynamics.

In light of these considerations, it is evident that the imaginary formations which suggest a division between physics and culture align with the discussions outlined in our first collaborative gathering. Basic education, which primarily emphasizes the resolution of mathematical exercises, and the undergraduate physics curriculum, which organizes knowledge according to segmentation and the reflective teacher model, both influence these representations—and these educational structures may shape the way undergraduates perceive physics as a cultural element.

Consequently, it is understandable that, despite two undergraduates establishing a direct connection between physics and culture, the prevailing educational conditions do not provide sufficient opportunities to foster a comprehensive understanding of the social, historical, ideological, and political dimensions of science. Zanetic (1990) argues that Physics, as culture, cannot be divorced from "external" factors, such as socioeconomic influences, ideological frameworks, the "definitions" of scientific methods, and the dynamic history of physics. These elements are essential for supporting experimentation, scientific theories, and their applications. Thus, physics assumes a pivotal role as a fundamental cultural component in the formation of individuals in contemporary society.

Final Considerations

Overall, this study aimed to explore key elements related to the initial training of physics educators, with the goal of outlining guidelines that facilitate sustainable scientific education based on the understanding of physics as culture.

The discourse analysis revealed two distinct projections within the imaginaries of undergraduate students: one sees physics and culture as distinct entities, while the other regards physics as an integral and indivisible component of culture.

The first viewpoint’s key conceptions, which separates physics from cultural contexts, clearly support discussions about the impact of basic education, which frequently concentrates solely on mathematical exercises, as well as the structure of the undergraduate physics program, which divides knowledge into different components.

This fragmentation leads to an understanding of physics as culture within the initial training of physics teachers, but that is incomplete and devoid of its essential cultural dimensions. Although two students managed to link physics with culture in the second projection, their training conditions fall short of offering a solid basis for cultivating a complete awareness of the diverse contexts that influence physics.

Finally, based on the premise that critical reflection offers a promising approach for the appropriation of physics as culture, there arises a need to reconsider the organizational structure of undergraduate programs. Such a reevaluation is essential to create educational environments that foster discussions and critical reflections on the historical, social, philosophical, and ideological contexts of physics as a cultural subject. Critical, transformative, and sustainable scientific education must be a part of physics teacher preparation programs from the start.

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Beyond Human Mentors – Exploring AI-Driven Reflection In Teacher Training

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This paper reports on integrating AI-based reflection coaches into a Physics Teaching & Learning Lab in pre-service teacher education and examines how students relate this support to supervision. The intervention provided structured experience with generative AI while scaffolding reflection across cycles of preparation, school-class visits, reflection, and adaptation. We conducted guided end-of-course interviews with 12 of 13 participants and analysed the data using content-structuring qualitative content analysis complemented by a deductive marker analysis of relationship-relevant qualities. Students largely reported little to no direct impact of chatbot use on their supervisory relationships with the course lecturers and predominantly conceptualized the chatbot as a tool rather than an independent supervisor. At the same time, their accounts invoked relationship-relevant qualities, especially closeness (limited by boundary-setting and restricted availability), relatedness (a low-pressure space enabling reassurance before approaching lecturers), and genuineness (overly validating interaction styles perceived as inauthentic). Overall, chatbots may support reflection and indirectly shape relational dynamics, but do not substitute authentic human experience in supervision.

Keywords: Teacher education, Generative AI, Teacher-student relationships

Introduction

Generative AI tools such as chatbots are rapidly becoming part of educational practice and, consequently, a relevant topic for teacher education (OECD, 2026). However, early evidence from our context suggests that many pre-service teachers still gain little systematic experience with AI tools in their university courses, and that this lack of experience matters: students without prior use tend to report lower perceived competence/self-efficacy and a more cautious attitude toward AI, whereas experience with AI use is associated with greater confidence and a higher likelihood of future use (Lutz et al., 2025).

Against this background, we designed the present course innovation with the intention to first, provide physics teacher trainees with the opportunity to engage with AI tools in a didactically meaningful, structured way; and second, to explore whether such tools can productively support processes that are known to be central for teacher professional learning, most notably reflection on practice. Reflection is a core component of many practice-based formats, yet it is also resource-intensive: it requires time, individual attention, and sustained guidance, which is difficult to provide consistently in university courses.

Our intervention is embedded in an iterative Teaching & Learning Lab course format in which students design and realize experimental learning stations and repeatedly revise them across several school-class visits (see **Figure** 1 for the overall sequence).

To strengthen the reflection phases within this cycle, we integrated AI-based reflection coaches (custom GPTs) intended to guide students through structured reflective dialogues and to support concrete adaptations for subsequent realizations.

While research and public discourse often focus on performance, ethics, or learning gains, an equally important – yet less frequently examined – dimension concerns relationships in teacher education. Mentoring and supervision are inherently relational, and introducing an AI tool into

reflective support raises a subtle question: even if students only perceive the chatbot as a tool, might their descriptions still reveal relationship-relevant qualities (e.g., perceived closeness, relatedness, or genuineness) that shape how supervision is experienced? Prior work in our project suggests precisely such a pattern: students tend to report little direct change in their relationship with human mentors, yet they also articulate relationally meaningful experiences with the chatbot interaction (e.g., neutrality, emotional relief, and authenticity as a boundary) (Damköhler et al., 2025).

This paper addresses the following research questions:

- RQ1: How do physics student teachers describe the impact of chatbot-based reflection coaching on their supervisory relationship(s) with course lecturers?
- RQ2: How do students conceptualize the chatbot as an interaction partner (e.g., human-likeness and underlying conceptions of AI)?
- RQ3: Which relationship-relevant qualities do students invoke, explicitly or implicitly, when describing chatbot-supported reflection and supervision?

To answer these questions, we conducted guided interviews with course participants and analysed the data using content-structuring qualitative content analysis complemented by a deductive marker analysis of relationship-relevant qualities.

Theory

AI Literacy

As suggested by Lutz et al. (2025), guided and targeted engagement with AI tools and the positive experiences that may result from such engagement can contribute to students' confidence in their own capability to use AI effectively. To describe these competencies more precisely, the concept of AI literacy has been developed in analogy to established literacy frameworks; e.g., digital literacy, computational literacy, data literacy, scientific literacy (Long & Magerko, 2020). In this view, AI literacy captures not only functional use, but also the understanding and critical evaluation of AI systems in educational contexts.

One operationalization of this construct is provided by the Meta AI Literacy Scale MAILS (Carolus et al., 2023), which conceptualizes AI literacy as a set of competencies related to using and applying AI, understanding AI, detecting AI, and reflecting on ethical implications of AI use. Furthermore, it contains a concept of AI self-efficacy (which includes aspects of AI problem solving and AI learning) and AI self-competency (which is based on AI persuasion literacy and AI emotion regulation). In the present study, this framework served primarily as a basis for designing interview prompts that elicit students' experiences with chatbot-supported reflection.

Teacher-Student Relationships

While AI literacy provides a useful framework for understanding competencies needed for responsible and effective AI use, the present paper additionally draws on research on teacher-student relationships and related constructs. This is because chatbot-supported reflection may be experienced not only as a functional tool interaction, but also in terms of relationship-relevant qualities such as perceived closeness, relatedness, and genuineness that can shape how reflective support and supervision are approached. This relational lens is further supported by the 'Computers Are Social Actors' (CASA) perspective, which suggests that people may respond to computer-based interaction using social scripts and expectations, even when they are fully aware that they are interacting with a machine (Nass et al., 1994). Importantly, meta-analytic findings indicate that both positive and negative teacher-student relationships show medium-to-large

associations with students' engagement (and smaller but still significant links to achievement), underscoring why relational quality is central for learning processes (Roorda et al., 2011).

Attachment Theory

From an attachment perspective, relationships with significant adults can function as a secure base that enables exploration and learning. In educational contexts, this is often operationalized via dimensions such as closeness (warmth and openness), conflict, and dependency; closeness captures whether an interaction climate supports trustful, open communication (Pianta, 1999, 2001). In our context, this lens helps interpret students' answers regarding boundaries, availability, and interpersonal nuance as conditions that may limit or enable closeness – regardless of whether the interaction partner is framed as a tool or a person.

Self-System Theory / Self-Determination Theory

Drawing on the Self-Determination Theory, the satisfaction of three basic psychological needs – autonomy, competence, and relatedness – is considered fundamental for the development of supportive relationships (Ryan & Deci, 2000). In supportive educational relationships, relatedness is fostered when learners feel accepted and psychologically safe; autonomy is supported when guidance is non-controlling; and competence is supported through structure and feedback that enables progress. Applied to reflective support, SDT helps capture why students might value a "low-pressure" space (relatedness/safety), benefit from structured prompts (competence support), yet still insist on human mentoring for authenticity and situated judgement (Roorda et al., 2011).

Learner-Centred Teacher-Student Relationship

Research on teacher-student relationships highlights that relational quality is not a "nice-to-have" but a robust correlate of students' engagement and learning. Meta-analytic work shows that affective relationship qualities – especially warmth and support – are consistently associated with students' engagement and, to a smaller extent, achievement (Cornelius-White, 2007). For this paper, TSR provides a vocabulary for describing how supportive interactions are experienced which includes empathy, warmth, genuineness, nondirectivity, higher order thinking, encouraging learning/challenge, adapting to individual and social differences (Cornelius-White, 2007).

Course Design

Course Sequence Of The Teaching & Learning Lab

As previously described, the Physics Teaching & Learning Lab (TLL) at the University of Würzburg is organized as an iterative course format that connects university-based preparation with authentic teaching-related experiences in a secure framework (Damköhler et al., 2025; Völker & Trefzger, 2011). Over the semester, students design and run their own experimental learning station and accompany small groups of school students working on hands-on physics tasks. The course follows a recurring cycle of preparation (preparatory phase) – visits by school classes – reflection – adaptation (see Figure 1).

Figure 1. Structure of the TLL



During the preparatory phase, students develop an inquiry-oriented station including materials, instructions, and prompts that are suitable for a short, self-contained learning unit. The station is

then implemented during a visit by a school class, where the TLL is operated in a station-based format: each station is typically completed in 30 minutes by small groups of school students, and each student tutor runs their station about four times across the visit.

After each class visit, the teacher trainees enter a reflection phase in which experiences from implementation are documented, discussed, and analytically processed. This reflection is typically supported by the two lecturers, who provide feedback and help connect observations to instructional goals and design principles. Based on these reflections, students adapt their stations in a targeted way before the next implementation. This cycle is repeated across three class visits, with exactly two weeks between visits, allowing students to iteratively refine their station design and their instructional practice across successive realizations.

Implementing AI-Based Reflection Coaches

The AI-based reflection coaching was integrated into the reflection and adaptation phases of the TLL cycle. After each visit by a school class, the course provides a structured opportunity to analyse the previous run and to derive concrete improvements for the next implementation. The revised format was supported by individual dialogue-based coaching from two AI reflection coaches, while the overall course structure (reflection followed by targeted adaptation) remained unchanged.

These sessions with the AI-based reflection coaches took place in the two scheduled reflection/adaptation sessions following the first and second class visits. The chatbot-led dialogues were designed to (a) structure students' retrospective analysis of their station realization, (b) prompt justification and elaboration to deepen reflection, and (c) support the development of feasible adaptations for the next class visit. The two coaches were used with different focal points: one coach emphasized an analytic reflection on the quality of the implementation, while the other coach additionally promoted the deliberate evaluation of alternative options and encouraged a critical stance toward AI-generated suggestions.

Following the individual coaching dialogues, reflections were brought back to the course context: students summarized and contextualized their insights and planned changes, and these were then discussed regarding their suitability for the course structure and supported by the lecturers. In addition to the AI use for coaching purposes, the implementation also included a meta-level engagement with the technology in which students exchanged experiences and reflected on further effects of the technology (e.g., perceived boundaries of AI support, ethical considerations, and potential implications for supervision in the TLL).

Design And Development Of The Reflection Coaches

The reflection coaches were developed as customized chatbots based on GPT-4 using the GPT development environment within ChatGPT. Their design followed a principle of aligning coaching prompts with clearly specified theoretical foundations and with an anticipated structure of productive reflection dialogues. For both coaches, relevant background materials were provided and integrated so that the chatbots could explicitly draw on them during the conversation. The first coach was based on the framework of basic dimensions of teaching quality (Praetorius et al., 2018), while the second coach was based on Korthagen's onion model (Korthagen, 2004), a framework addressing teacher personality and professional development.

For each coach, the team first anticipated the course of a plausible coaching conversation based on the underlying theory and then decomposed it into smaller conversation blocks (i.e., coherent phases with specific functions such as eliciting a description of the implementation, probing for explanations, generating alternatives, or consolidating an action plan). The chatbots' behaviour was then specified through a combination of (1) the integrated theoretical background materials

and (2) systematic prompting: a precise role description (reflection coach), a set of general behavioural rules (e.g., guiding the dialogue, asking follow-up questions, supporting structured reflection), and block-specific instructions defining the intended interactional moves and goals within each phase of the dialogue.

Before student use, both coaches were subjected to pre-testing in simulated coaching conversations across different scenarios by several test persons. This iterative testing served to check whether the chatbots' guidance reliably instantiated the intended coaching structure, whether follow-up questions supported depth rather than superficial agreement, and whether the dialogue design consistently led to the intended outcome – namely, a justified reflection and a concrete plan for adaptation before the next class visit.

Method

Course Context And Sample

The study was conducted in the summer semester of 2024 in a Physics TLL at the University of Würzburg. The course was attended by 13 pre-service teachers; N = 12 of them participated in the evaluation study. Participation in the interviews was voluntary.

Data Collection

Data were collected through guided, semi-structured interviews which lasted approximately 10 to 15 minutes and were conducted at the end of the semester by the two course lecturers. The interview guide was developed with reference to the previously described MAILS framework (Carolus et al., 2023) and adapted to the specific course context. Rather than administering MAILS as a test, selected item formulations were used as prompts to recall students' experiences and perspectives regarding chatbot-supported reflection, including perceived differences between human and AI interaction and the perceived influence of chatbot use on their supervision-related conversations. For example, the MAILS item "I can distinguish if I interact with an AI or a 'real human'" was contextualized into an interview question about differences between a chatbot conversation and a conversation with a real person.

All interviews were audio-recorded and transcribed. Transcripts were lightly edited for readability (e.g., reducing fillers) without changing the intended meaning of statements.

Content-Structuring Qualitative Content Analysis

The material was analysed using content-structuring qualitative content analysis following Kuckartz und Rädiker (2022). As recommended in this approach, we defined the coding unit as a single sentence (i.e., the smallest textual unit to be assigned to a category), while consecutive sentences belonging together contextually served as the context unit. In line with Kuckartz, multiple coding was allowed.

To address the aims of the present paper, analysis proceeded in two coding passes.

First Coding Pass: Explicit Topical Categories (Guide-Based, Inductively Refined).

In the first pass, we organized students' explicit statements using a set of deductive top-level categories derived from the interview guide. These top-level categories captured the main topics addressed by the students and provided a structured overview of how students articulated their views. The deductive top-level categories were: (1) "Independent supervisor?", (2) "Differences to a real conversation?", (3) "Influence on conversations with lecturers?", and (4) "Changed relevance of lecturers?". Following the logic of content-structuring analysis, these categories were then refined inductively: subcategories were developed from the interview material to

capture the diversity of students' perspectives. Given the relatively small number of interviews and the high thematic variety, the category system was developed based on the entire dataset.

Second Coding Pass: Deductive Marker Analysis Of Relationship-Relevant Qualities.

A second coding pass focused on relationship-relevant qualities that students referred to implicitly or explicitly, even when they did not explicitly frame their statements as 'relationship' talk. This step was motivated by the observation that students often stated that chatbot use had little or no direct impact on their supervisory relationships, while simultaneously describing interaction qualities that are central to theories of teacher-student relationships. For this reason, we conducted a deductive marker analysis using a set of relationship-quality markers derived from three theoretical perspectives: attachment theory, learner-centred teacher-student relationship research, and self-system theory. Based on these frameworks, we developed a formalized codebook containing short definitions and anchor examples for each marker (e.g., closeness, relatedness, genuineness, higher-order thinking, encouraging learning). The codebook was used to identify segments indicating these qualities across the interviews.

Importantly, we did not build separate category families for different "targets" (e.g., student-chatbot vs. student-mentor). Instead, the same marker set was applied to segments referring to the chatbot, to lecturers, and to statements that remained unspecific with respect to a relationship partner. This approach reflects our analytic interest in students' relational expectations and interaction qualities in the context of reflective support, which can be articulated without explicitly naming the relationship partner.

Coding was conducted primarily by one researcher. Selected segments and ambiguous cases were discussed within the two-person research team until a shared interpretation was reached.

Results

All interview quotes were translated from German by the authors for publication. The translations aim to preserve meaning and tone.

RQ1 Described Impact On Supervisory Relationships

Most students described little to no direct impact of the chatbot conversations on their supervisory relationships and conversations with the course lecturers. When asked about changes in the lecturers' relevance, nine of twelve students reported no (n = 7) or only minor (n = 2) changes and highlighted the continuing value of human supervisors *("I see the AI as a helpful tool, but your practical experience is hard to match – especially in the Teaching & Learning Lab setting. So, overall, I wouldn't say it changed much."* – Patrick). Students often framed chatbot use and lecturer conversations as serving different functions: chatbot dialogues supported individual reflection on one's own station, whereas lecturer conversations were described as more situational, experience-based, and oriented toward practical problem solving *("What I talked about with you was something completely different from what I talked about with the AI."* – Caro).

A smaller group reported indirect links between chatbot use and lecturer interaction. Three participants described the chatbot sessions as providing conversation triggers (*"[...] it didn't really influence things, but it did provide new input for topics to talk about [...]"* – Martina) and two described a pre-relief effect – using the chatbot to voice uncertainties or "stupid questions" without embarrassment before approaching lecturers *("I think I was more likely to ask the AI a few 'stupid questions'[...]"* – Saph). One participant explicitly reported a more relaxed relationship with lecturers *("I think I would have felt a bit more under observation if I had the entire conversation with you."* – Emily).

Several students also noted practical constraints, particularly limited time to implement or discuss chatbot suggestions with lecturers *("[…] it didn't feel like we truly had enough time afterwards to implement what came out of the AI session"* – Caro]), and a few preferred more direct human exchange (e.g., small-group discussions) *("I actually would have preferred a conversation with you in a small group of four."* – Franka).

RQ2 Conceptualization Of The Chatbot

Overall, students predominantly conceptualized the chatbot as a tool-like technology rather than an independent 'person'. Typical descriptions framed it as a programmed system, a machine, a search-engine-like resource, a tool, a digital extension of the lecturers, or a neutral instance for thinking through one's own practice. At the same time, a small number of accounts portrayed the chatbot interaction as a relatively separate field of support – notably because students engaged with it without involving the lecturers – while still emphasizing that this did not generally apply to all situations and could not replace the interpersonal qualities of human supervision (*"[...] in the sense that you're texting it, it is something of its own, because we didn't involve you [the lecturers] at all. […] In this case, it worked well."* – Annika). A frequently mentioned difference to 'real' conversation concerned the chatbot's interaction style: although it had been instructed not to evaluate or provide feedback, students experienced it as overly validating and often strongly praising, and thus as qualitatively distinct from human feedback.

RQ3 Relationship-Relevant Qualities

Across the interviews, students' remarks frequently invoked relationship-relevant qualities, most prominently closeness, relatedness, and genuineness. Regarding closeness (warmth and openness), several students emphasized a clear boundary between interacting with a machine and with a person, which for them limited the degree of relational openness (e.g., *"You still must distinguish. You're talking to a machine, not to a human being. That difference must remain."* – Alexa). Beyond the human-machine boundary, some students link limited closeness to the chatbot's restricted availability. As one student noted, the AI could only be used *"for a very limited period of time,"* which did not necessarily coincide with moments when questions emerged, and they explicitly wondered how the experience might differ if it were *"permanently available"* (Saph). Others pointed to missing interpersonal nuances such as implicit undertones in communication (e.g., *"What the AI can't do is capture what's implicit. The undertone you pick up when people talk to each other. I don't think AI can do that."* – Annika), while only very few suggested that the interaction could, in specific moments, resemble communication with a person (e.g., *"No. In the end, it could just as well have been a human I was communicating with"* – Peter).

With respect to relatedness, students described the chatbot interaction as a safe, low-risk environment that could provide emotional reassurance, particularly in phases of uncertainty (e.g., *"At the beginning I was really lost about how to implement things, and the AI did give me a bit of emotional reassurance."* – Franka).

Finally, genuineness emerged as a salient boundary condition: some students criticized the interaction style as overly validating and strongly praising, which they experienced as inauthentic (e.g. *"Yes, because of the excessive praise. I found that really irritating at times"* – Peter).

In addition, students also mentioned that chatbot use could support higher-order thinking (e.g., by prompting reflection and critical evaluation of outputs) and encouraging learning (e.g., through structuring and guiding the reflective process), even though these aspects were typically described as complementary rather than substituting human support.

Discussion

Overall, the findings suggest that the chatbots functioned primarily as supportive tools for reflection, rather than being perceived as an independent supervisory figure. At the same time, students' answers contained multiple relationship-relevant cues – even when participants explicitly stated that chatbot use had little impact on supervisory relationships. In particular, students' references to closeness, relatedness, and genuineness indicate that chatbot-supported reflection can intersect with relational dynamics in teacher education in subtle ways: restricted availability and a clear human-machine boundary limited perceived closeness; the chatbot could still provide a low-pressure space for articulating uncertainty; and interaction styles perceived as overly validating highlighted genuineness as a decisive boundary condition. Overall, these patterns suggest that it is worthwhile looking beyond direct claims of 'relationship change' and pay attention to the relational qualities students mention when describing reflective support.

These insights translate into concrete implications for course design. First, availability is not only relevant for relational reasons but also pragmatically: if reflective tasks emerge outside narrow time windows, restricted access may prevent students from using the tool in a moment of need and may thereby limit closeness. In a subsequent iteration of the course, we therefore reduced constraints on availability. Initial feedback from students in that follow-up project (Herz et al., 2025) points in the direction that more flexible access can support meaningful use. Second, our results underline the importance of combining chatbot reflection with human supervision. Several students described the two support formats as operating "either-or," with too little time to discuss and implement insights. Future designs should therefore create structured opportunities to jointly discuss, validate, and translate chatbot outputs into concrete adaptations – for instance in small-group debriefings with lecturers – so that AI support complements rather than competes with human mentoring.

Finally, the results also call for a brief cautionary note regarding students' conceptions of AI. While many students framed the chatbot as a programmed tool, one described it as a "neutral instance." Even if meant in the sense of "non-judgmental," such framing may unintentionally reduce vigilance toward potential biases or limitations of AI-generated suggestions. This reinforces the need to embed chatbot use in explicit AI literacy work – particularly around critical evaluation of outputs and an awareness that 'helpful' and 'neutral' are not the same. Importantly, students themselves strongly emphasized that, for complex real-world teaching problems, chatbot suggestions require careful examination and cannot substitute the authenticity and experience-based judgement of human supervisors. In this sense, chatbots may scaffold reflective processes, but they do not replace what students perceive as uniquely valuable in supervision: authentic human experience.

Conclusion And Outlook

The present study suggests that our chatbot-based reflection coaching was primarily experienced as supportive scaffolding rather than an independent form of supervision, while students' accounts nevertheless contained relationship-relevant statements. At the same time, conclusions are constrained by several limitations: the study draws on a small sample from a single course (N=12), relies on end-of-course self-reports, and the interviews were conducted by the course lecturers, which may have shaped how openly participants discussed critical views. In addition, coding was conducted primarily by one researcher.

Future work will therefore extend beyond interview accounts by **analys**ing students' recorded reflection products given immediately after teaching-related experiences, allowing us to examine whether chatbot use is associated with changes in the structure and depth of reflection and in the

specificity of subsequent adaptations. Further iterations should also systematically change key design parameters – most notably availability and the structured integration of chatbot reflection with lecturer-led small-group debriefs – to identify configurations that support meaningful use without weakening human supervision. Finally, triangulating interviews, reflection products, and (where available) chatbot interaction traces in a longitudinal design can clarify how relational expectations and AI literacy practices (including critical evaluation and assumptions of "neutrality") develop through repeated, guided use.

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Transparency Statement

In producing this manuscript, generative AI tools were used to support literature research, outlining, parts of the writing process, and – on an exploratory basis – data analysis. All uses were monitored and verified by the authors, who take full responsibility for the content.

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Analysis Of Physics And Chemistry Pre-Service Teachers' Perceptions About Their Teaching Identity And Professional Development

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Developing a Teaching Professional Identity (TPI) is crucial for effective teaching practice, particularly during initial teacher education. This study explores the perceptions of eight preservice secondary science teachers (PSSTs) about their professional development during their Master's in Education program (MEd), specifically examining how self-reflection on teaching competencies contributes to their identity construction. Through a qualitative case study approach, we analysed PSSTs' responses to an ad-hoc survey, focusing on nine teaching competencies and their relationship with five key factors affecting TPI (teaching experience, motivation, self-image, Master's expectations, and task perception). In general, the analysis reveals that PSSTs showed a balanced awareness of their strengths and challenges. Findings suggest that PSSTs' identity formation is significantly influenced by their practical teaching experiences and self-image, revealing the important role of initial teaching education programs in supporting their transition into teaching careers. Hence, while teaching experience plays a crucial role in shaping their confidence and competencies, there is a clear recognition of the need for continuous self-assessment, positive attitudes, and the development of both personal and social skills to foster a harmonious and effective learning environment. In short, these results highlight the need for a more comprehensive approach in initial teacher education programs, where the development of both professional skills and personal identity is nurtured through reflection, experience, and positive engagement with the teaching profession.

Keywords: Pre-service teacher education, teacher identity, professional development

Introduction

The International Teaching and Learning Survey (TALIS) (Organisation for Economic Co-operation and Development [OECD], 2025) reveals that teachers who have recently graduated report feeling insufficiently prepared, both in terms of subject-matter knowledge, pedagogical and practical aspects, to teach the subjects for which they are responsible. Additionally, the growing demands for equity and inclusion (Karousiou et al., 2019) and the educational shift towards personalised and student-centred pedagogies (Schleicher, 2018) represent a challenge in defining teachers' roles, leading to graduated teachers reporting high levels of stressed in their early years (OECD, 2025). This situation leads some in the secondary teaching workforce to perceive themselves not as subject teachers but rather as graduates in a scientific discipline who transmit content. As a result, a spontaneous approach to teaching predominates, grounded in prior experience as learners, directly impacting the construction of their teaching identity, their instructional practices, and their professionalism (Imbernón, 2019).

Research on teacher identity is therefore essential because, as Wenger (1998) explains, it examines "how learning changes who we are" (p. 5). Moreover, the concept of identity enables teachers to reflect on the relationship between the individual and the world, thereby addressing the role of context and valuing the sociocultural nature of learning (Gee, 2000). Nevertheless, despite the existence of review studies on teacher identity, further research is required to ensure a specific focus on the identity of science teachers (Avraamidou, 2014), particularly during their initial training period. This interest is grounded in the idea that, in order to make the transition from student to teacher, pre-service science teachers (PSSTs) must not only acquire a set of skills,

knowledge, and an understanding of pedagogical approaches, but also create and recreate their self-image as active members of a professional community—an aspect that is directly related to the construction of their teacher identity (Sutherland et al., 2010).

In light of the above, promoting and fostering the development of strong teacher identities is essential for teachers themselves, the research community, and educational policy. The benefits of analysing the professional identity of science teachers (TPI) are directly linked to students' learning success, the strengthening of teachers' self-image, and the assurance of the development of effective educational policies (Suárez & McGrawth, 2022).

Theoretical Framework

In the teaching-learning process, teachers are a key agent with a direct impact on students' learning and development (Jennings & Greenberg, 2009), leading both society and educational systems to revalue the teaching profession in a context characterised by constant change and fluctuation (Nias, 2014). As a consequence, in recent years, there has been growing interest in understanding teachers' professional lives through the study of their TPI and its influence on teaching quality, motivation to teach, commitment to the profession, good pedagogical practices, and decision-making in school contexts (Beauchamp & Thomas, 2009; Buchanan, 2015). For teachers, understanding their TPI can strengthen teaching practice insofar as it aligns with fundamental questions such as "who am I?" or "what should I do?" (Mockler, 2020), which directly influence pedagogical decision-making and teacher–student relationships.

TPI encompasses teachers' perceptions, beliefs, and attitudes about their professional role (Cordingley et al., 2019), significantly influencing classroom practices and policy implementation (Karousiou et al., 2019). Although, over the years, researchers have approached TPI from different theoretical perspectives and proposed various definitions, there are some commonalities widely acknowledged, such as its complexity and multidimensionality, its evolution with personal and professional experiences, and its variation across individuals and cultures (Hanna et al., 2019).

Within the context of teacher education, the sociocultural approach results particularly valuable, as it allows for a broader understanding of professional development that goes beyond the acquisition of knowledge and technical skills (Gee, 2000). Furthermore, this approach has facilitated analysis of how teachers perceive themselves, how they are recognized by others, and how factors such as gender, personal histories, and prior experiences influence the construction of their professional identity (Avraamidou, 2014).

Nevertheless, research on pre-service teachers' TPI remains at an early stage in understanding how these identities are constructed, which factors influence their transformation, and what role they play in motivating both teachers and students to learn (Schutz et al., 2018). This gap highlights the need for more integrative frameworks that connect teacher identity with key dimensions of professional practice, development, and effectiveness across changing educational contexts.

In an era characterized by rapid change and uncertainty, teachers face diverse expectations from multiple stakeholders while navigating complex educational transformations (Nias, 2014), making essential to promote ever since teacher education the construction of a robust TPI to respond to these challenges while maintaining high-quality instructional practices effectively ensuring in this way educational quality and successful teaching careers.

For doing so, it becomes fundamental to research into key factors and domains shaping TPI from teacher education program, analysing, among others, the influence of motivation (drive to be or

become a teacher), self-image (how individuals view and feel as teachers), self-efficacy (belief in their capability to perform their teaching activities effectively) or task perception (beliefs about what a teacher considers to be good teaching) (Suárez & McGrath, 2022).

These TPI elements intersect with teachers' competencies, affecting their professional development and classroom effectiveness. Hence, the relationship between teaching competencies and TPI becomes particularly relevant when examining how teachers negotiate their professional roles and responsibilities. Studies suggest that teachers with well-developed professional identities demonstrate a greater capacity to implement educational innovations and maintain a commitment to their practice (Sachs, 2016). This interplay between competencies and identity formation provides a crucial framework for understanding teacher professional development and effectiveness in contemporary educational settings.

Aims And Research Questions

With the purpose of contributing to the growing body of research on TPI while offering insights into effective teacher preparation and professional development strategies, this study explores the interconnection between teaching competencies and TPI development. Focusing on how PSSTs' experiences and initial teacher education influence their professional identity formation, we aim to answer the following research question: What are the perceptions of PSSTs about their teaching professional development during their initial training stage, and how does self-reflection on teaching competencies contribute to the construction of teachers' identity?

Methodology

Participants

This research was developed as a case study design with 8 PSSTs of the MEd from the University of Málaga, from the speciality of "Physics and Chemistry". All participants held a bachelor's or a master's degree in either science or engineering, which is a requisite to enroll in the MEd. The demographic composition of the group included three males and five females, with ages ranging from 25 to 35 years.

Research Instrument, Data Collection And Analysis

Through an *ad-hoc* survey-type task, PSSTs were asked to identify and justify their professional development level for the teaching competencies (TC) promoted during the MEd, related to curriculum assessment (TC1), professional communication (TC2), social climate (TC3), reflection innovation (TC4), institutional culture (TC5), collaborative decision-making (TC6), instructional design

We collected data through an online survey during the 2022/2023 (PSST1-PSST4) and 2023/2024 (PSST5-PSST8) academic years. We then proceeded to develop a qualitative analysis of PSSTs' responses individually using coding techniques performed with the Atlas.ti software (version 25.0.1). Thus, the researchers and co-authors of this communication read the individual responses and co-related them to factors linked to TPI development, particularly the previous experiences of the teachers and their initial teacher education, following the Suárez and McGrath (2022) framework. Hence, based on common patterns and key aspects found in the PSSTs' responses, we then coded and categorised data independently within domains and factors most affecting TPI in teacher education (teaching experience [TE], motivation [MO], self-image [SI], MEd expectations (instead of job satisfaction) [ME] and task perception [TP]), finally negotiating the coding consensus (Creswell, 2013).

Findings

Table 1 illustrates how PSSTs' responses were classified each teaching competencies described in the survey and the subsequent categorisation according to the main factors affecting TPI, also providing an example of response.

Table 1. Examples of the categorization of PSSTs' responses within each teaching competence and TPI factor.

PSST	TEACHING COMPETENCIES AND FACTORS AFFECTING TPI
PSST 5	**Teaching competence:** *Affective interaction (TC8)*
	TPI Factor: *MEd expectations (ME)*
	Response: *"I believe this attitude is developed through practice and experience, so I hope to improve in the best possible way during the remaining months of my master's."*
PSST 6	**Teaching competence:** *Reflection innovation (TC4)*
	TPI Factor: *Motivation (MO)*
	Response: *"Although I am not very familiar with the subject, I think I can manage to give feedback and try to improve the proposal when necessary."*
PSST 8	**Teaching competence:** *Professional communication (TC2)*
	TPI Factor: *Self-image (SI)*
	Response: *"I do consider that I have this competence more developed since although I have not yet worked as a teacher, I have given many talks and workshops to secondary school students, and I have some practice expressing myself in writing and orally with them."*
PSST 7	**Teaching competence:** *Social climate (TC3)*
	TPI Factor: *Teaching experience (TE)*
	Response: *"I believe it is important to have social skills to create a positive learning environment and promote coexistence in the classroom. It is something I don't have much experience in, but I believe it can improve over time."*
PSST2	**Teaching competence:** *Curriculum assessment (TC1)*
	TPI Factor: *Task perception (TP)*
	Response: *"Regarding the evaluation, I consider it one of the most difficult points to carry out, since we not only have to take into account the grade of an exam, but also their previous level, the student's performance in class, their proactivity, etc."*

Table 2. Relationship between the nine teaching competencies and the factors influencing TPI.

TEACHING COMPETENCIES	FACTORS AFFECTING TPI					TOTAL (per TC)
	TE	**MO**	**SI**	**ME**	**TP**	
TC1 Curriculum assessment	5	1	6	2	3	17
TC2 Professional communication	6	2	6	0	2	16
TC3 Social climate	2	4	4	0	6	16
TC4 Reflection innovation	3	2	4	3	2	14
TC5 Institutional culture	5	2	3	1	0	11
TC6 Collaborative decision-making	2	0	4	0	8	14
TC7 Instructional design	2	6	2	3	0	13
TC8 Affective interaction	3	5	2	1	2	13
TC9 Evidence-based improvement	3	0	4	1	8	16
***TOTAL** (per factor)*	**31**	**22**	**35**	**11**	**31**	130

Table 2 provides an overview of the relationship between the nine teaching competencies and the factors influencing TPI as perceived by the eight PSSTs, relating the number of mentions of each factor within each teaching competence. Notably, collaborative decision-making (TC6) and evidence-based improvement (TC9) show strong connections to task perception (TP) (8 mentions

each), while professional communication (TC2) has strong links to both teaching experience (TE) and self-image (SI) (6 mentions each), and instructional design (TC7) shows a strong connection to motivation (MO) (6 mentions). This distribution also suggests that specific competencies, particularly those related to curriculum and assessment (TC1), tend to engage multiple identity factors simultaneously.

In total, PSSTs included up to 130 mentions in their survey responses about the teaching competencies (Table 3), mainly concerning self-image (35), teaching experience (31) and task perception (31). On the other hand, motivation (22) and MEd expectations (11), were the less mentioned competencies in the study, respectively.

Table 3. Frequency of mentions emerged from the analysis per PSST.

FACTORS AFFECTING TPI	PPSTs								TOTAL (per category)
	1	2	3	4	5	6	7	8	
MEd EXPECTATIONS (ME)	**0**	**5**	**0**	**1**	**1**	**1**	**3**	**0**	**11**
Educational methodologies	0	2	0	1	1	0	0	0	4
Teaching work	0	0	0	0	0	1	2	0	3
Functioning of the educational institution	0	1	0	0	0	0	1	0	2
Observation	0	1	0	0	0	0	0	0	1
Participation	0	1	0	0	0	0	0	0	1
MOTIVATION (MO)	**4**	**2**	**3**	**3**	**3**	**1**	**5**	**1**	**22**
Intention to improve	2	1	2	0	3	1	5	1	15
Interests	0	1	1	3	0	0	0	0	5
Teaching professional capacity	2	0	0	0	0	0	0	0	2
SELF-IMAGE (SI)	**8**	**0**	**3**	**5**	**2**	**7**	**1**	**9**	**35**
Self-assessment	3	0	2	4	2	5	1	9	26
Personality	2	0	1	1	0	2	0	0	6
Curricular aspects	1	0	0	0	0	0	0	0	1
Oral expression	1	0	0	0	0	0	0	0	1
Written expression	1	0	0	0	0	0	0	0	1
TEACHING EXPERIENCE (TE)	**2**	**3**	**4**	**3**	**3**	**7**	**3**	**6**	**31**
Lack of teaching experience	2	1	1	0	1	3	2	4	14
Previous teaching experience	0	1	3	3	2	4	1	2	16
Teaching resources	0	1	0	0	0	0	0	0	1
TASK PERCEPTION (TP)	**5**	**9**	**2**	**6**	**2**	**0**	**5**	**2**	**31**
Classroom management	1	2	1	0	1	0	0	1	6
Teacher collaboration	1	1	0	1	1	0	1	1	6
Attitude	2	2	1	3	0	0	1	0	9
Teaching and learning process assessment	1	2	0	0	0	0	2	0	5
Teacher-student relationship	0	1	0	1	0	0	0	0	2
Pedagogical methods	0	1	0	1	0	0	1	0	3
TOTAL (per PPST)	19	19	12	18	11	16	17	18	130

With reference to the five main factors affecting TPI, Table 3 shows the different subcategories encompassed within each of these factors. Regarding **self-image**, 'self-assessment' stands out as the main subcategory (26 mentions), highlighting the value of self-awareness and personal reflection in the construction of their professional identity. Concerning **teaching experience**, the results reveal a closely balanced division of opinions between 'Lack of experience' (17 mentions) and ‘Previous teaching experience' (16 mentions), reflecting the contrast between initial insecurity and the importance attributed to prior non-formal experiences in the development of their competencies. In terms of **task perception**, most responses highlight the attitude with which

PSSTs approach the teaching profession (9 mentions), emphasising a positive attitude toward overcoming challenges, followed by 'Classroom management' and 'Teacher collaboration' (6 mentions each), which indicates that the PSSTs acknowledge the importance of fostering a structured and collaborative environment that promotes active learning. Subsequently, with respect to **motivation**, the PSSTs highlight their intention to improve (15 mentions) their personal skills to ensure the success of the teaching-learning process, as well as their social skills, in a way that guarantees harmony in the classroom environment. Finally, the PSSTs express, as **expectations of the MEd**, the need to improve their training regarding new educational methodologies (4 mentions) and teaching practices (3 mentions), in order to adapt to new educational needs and ensure the success of the learning process.

Conclusions And Implications

This study examines PSSTs' perceptions of their professional development through a qualitative analysis, correlating teaching competencies and five key factors defining Teaching Professional Identity (TPI): teaching experience, motivation, self-image, MEd expectations, and task perception. The findings of this study lead us to make the following conclusions, which should be considered with caution due to the reduced number of participants in this case study.

Results show that PSSTs believe self-reflection, particularly through self-assessment, is crucial for building their professional identity. Likewise, the study highlights the value that PSSTs attribute to their own capabilities, limitations, and progress, revealing that the construction of professional identity is not solely the result of the accumulation of experience, but rather a continuous process of renegotiating their self-perception as teachers in relation to their competencies, expectations, and emotions. In this sense, reflection on one’s own teaching self-image emerges as a key mechanism for the development of TPI.

Teaching experience plays a key role, as PSSTs experience tension between initial insecurity due to lack of experience and the value they place on prior experiences. In this context, offering early, guided, and diverse teaching practice opportunities within initial teacher education programs is essential to help PSSTs connect theoretical content with classroom realities, thereby progressively strengthening their sense of professional competence and belonging.

Regarding task perception, a positive attitude toward challenges, classroom management, and teacher collaboration are key elements in shaping their identity. PSSTs also emphasize their motivation to improve both personal and social skills, highlighting the importance of comprehensive training that covers both professional and personal competencies.

Overall, this study underscores that reflection on teaching competencies and fostering an educational environment that allows PSSTs to assess and develop their abilities are essential for building a strong professional identity. In this regard, initial teacher education programs should create spaces for self-reflection and competency development, facilitating a successful transition into teaching practice and long-term professional success. This approach has important implications for the design of teacher training programs, which should integrate both technical competencies and the personal and reflective development of future teachers. Along these lines, such programs should adopt an integrated approach to professional development, articulating teaching competencies with factors linked to TPI and providing structured spaces for reflection, the promotion of teaching experiences, and attention to the socioemotional dimension, thus contributing to the development of a solid TPI. In this regard, the identification of key domains of professional identity can be used as a practical framework to guide assessment processes, course design, and reflective practices in initial teacher education, reinforcing the intentional development of TPI (Hanna et al., 2019).

Finally, despite the limitations derived from the reduced sample size, this research offers a competency-based perspective on the development of TPI during the initial training of science teachers. Future studies could extend this work through larger and more diverse samples, as well as comparative studies across disciplines and/or educational contexts. Such approaches would allow for a deeper understanding of how teaching competencies and professional identity construction interact, contributing to the design of teacher education programs that foster competent, reflective, and professionally committed teachers.

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Pre-Service Physics Teachers' Conceptions About What It Means To Understand Physics: A Phenomenographic Study

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The development of conceptual understanding is a long-standing goal of science education. However, a gap exists in the literature regarding what pre-service physics teachers' conceptions are of what it means to understand physics. Given the importance of teachers' epistemic conceptions for shaping their pedagogy, this gap is surprising. This study employed phenomenography to determine the qualitatively various ways that pre-service physics teachers conceptualize what it means to understand physics. Phenomenography is a second-order approach to research in which conceptions, (a) are viewed as being the product of interactions between humans and the world around them, and (b) arise from a human being's thinking about their external world. Fourteen pre-service physics teachers were interviewed individually for around thirty minutes each regarding their experiences as physics majors and their thoughts about what they considered it meant to understand physics. Five categories of description emerged from the analysis: (1) feeling, (2) applying, (3) making meaning, (4) communicating, and (5) accumulating. The first four categories occupy a higher level in the outcome space than the 'accumulating' category, as students reported that 'applying' and 'making meaning' were contingent on processes represented by the two sub-categories of 'accumulating.' The potential value of these findings is outlined.

Keywords: Phenomenography, physics, understanding.

Literature and Study Rationale

The understanding of concepts is closely related to high quality and/or in-depth learning. In science education there has been consistent attention to conceptual understanding and its development (e.g., Driver et al., 1994; Potvin et al., 2020) and conceptual change (e.g., Duit & Treagust, 2012; Lin et al., 2019). In this paper, however, the attention is on individuals' conceptions of understanding, itself, rather than on what it means to understand any particular science concept.

Previous research seeking individuals' views on what it means to understand has been reported. These studies employed phenomenography. The concept of understanding was identified by Marton et al. (1993), and Säljö (1982) as one of six conceptions of learning. Irving and Sayre (2012) investigated eighteen university physics students' conceptions of understanding and reported, similar to Waterhouse and Prosser (2000), that individuals understanding was when one could use and apply knowledge, and that one's level of understanding was determined according to different levels of task requirement and context complexity.

In phenomenographic research in science education, Zhao (2015) explored mainland Chinese students' conceptions of learning science. Lukie (2021) explored and compared high school physics students,' high school physics teachers,' and university physics professors' conceptions of what it means to understand physics. He reported five non-hierarchical categories: feelings, achievement, communication, making meaning, and application. The variations between the groups of participants related to their levels of knowledge, domain expertise, experience, and roles.

There is little, if any, research regarding pre-service science teachers' conceptions of what they consider understanding to be. Given that conceptions of understanding can be linked to teacher pedagogy, curriculum interpretation, learning processes, and domain expertise, the research reported in this paper is timely. It is important that teachers and their students have a shared, consistent view of what it means to understand science subjects. There should be a common epistemic foundation that can be shared and communicated between them. Otherwise, the purposes of teaching and learning might not be similar or identical between classroom participants. This study investigated pre-service physics teachers' conceptions of what it means to understand physics.

Research Design

Phenomenography: An Overview

Phenomenography is a "research method for mapping the qualitatively different ways in which people experience, conceptualize, perceive, and understand various aspects of, and phenomena in, the world around them" (Marton, 1986, p. 31). Phenomenographers adopt a second-order approach to research; their description of a phenomenon is based on the experience/s of that phenomenon as described by others (Marton & Booth, 1997; Trigwell, 2006). Marton (1986) suggests that "each phenomenon, concept, or principle can be understood in a limited number of qualitatively different ways" (p. 30). Phenomenographers attempt to identify and categorize the various, multiple conceptions that a population might have for a phenomenon and describe the variations in those conceptions. These categories of conceptions are presented as the 'outcome space' that represents the minimum number of categories that explain all the variations in the data. The outcome space should, (a) reveal something distinct about how the phenomenon is experienced, (b) present each category in its logical relationship with other categories, and (c) present the fewest number of categories that can represent the data and its analysis (Marton & Booth, 1997). This study aimed to determine, represent, and explain the outcome space representing pre-service physics teachers' conceptions of what it means to understand physics.

Participants, Data Collection, And Analysis

Fourteen pre-service teachers, physics majors enrolled in a Bachelors of Education degree at a large North American comprehensive university, consented to participate. Data were collected using semi-structured interviews of around 30 minutes each during which the participants answered open-ended questions (Dunkin, 2000, Bowden, 2005, Åkerlind, 2005a) about what they considered it meant to understand physics and about their experiences as physics learners. The interviews were transcribed and analysis began with the transcripts being read numerous times while listening to the audiotape in "to clarify what the participant meant" when responding to the questions (Åkerlind, 2005b, p. 328). The phenomenon in question, i.e., understanding physics, was then "narrowed down to and interpreted in terms of selected quotes" (Marton, 1986, p. 42). The selected quotes and their interpreted meanings were compared to identify sources of variation and agreement, and to ascertain which could be grouped together and which could remain separate. After these processes had been undertaken several times, labels for the categories of conceptions were determined and the categories were arranged (in the outcome space) in a way that respected and reflected the pre-service teachers' self-reports regarding what they considered it meant to understand physics.

Results and Discussion

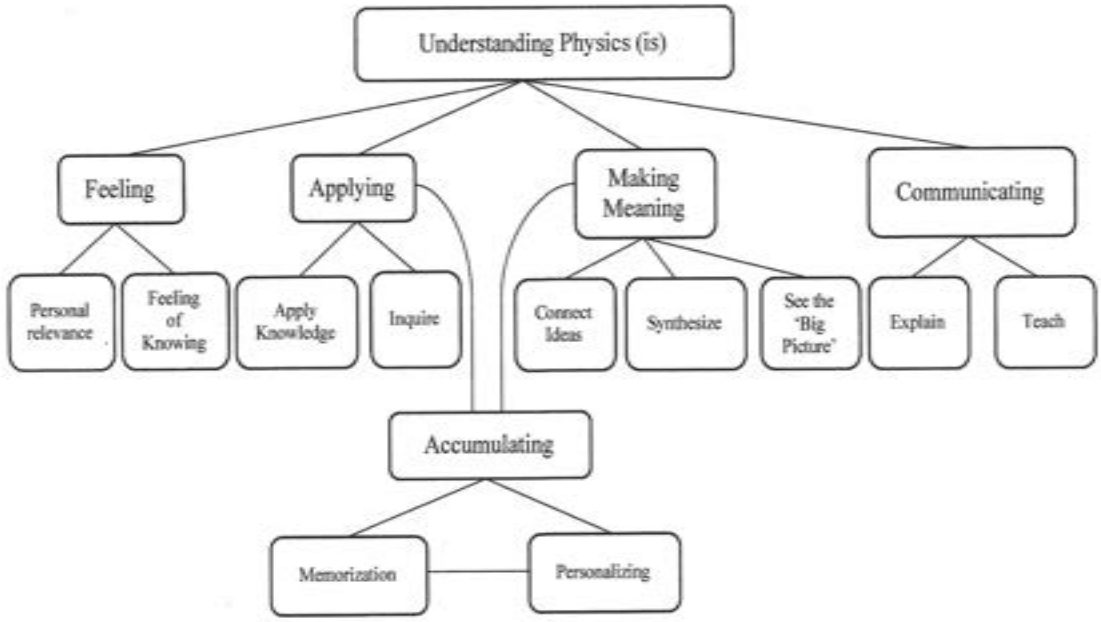
Five conceptions of understanding physics are evident: Feeling, Applying, Making Meaning, Communicating, and Accumulating. Eleven sub-categories emerged: Personal Relevance,

Feeling of Knowing, Apply Knowledge, Inquire, Connect Ideas, Synthesize, See the 'Big Picture,' Explain, Teach, Memorization, and Personalization. The structure of the outcome space (Figure 1) is hierarchical. This is in contrast to the outcome spaces reported by Lukie (2021) and Zhao (2015) who both reported circular outcome spaces. However, it is consistent with those outcome spaces reported by Irving and Sayre (2012) and Waterhouse and Prosser (2000). In outlining these conceptions, examples of students' interview comments are provided to illustrate the researcher's interpretations.

Accumulating

The participants said that what it means to understand Physics was to accumulate information and memory elements via *Memorization*, which involved conscious attention to information retention, often at a surface level, as exemplified by comments such as "understanding involves…taking notes of the key terms, doing definitions of those terms, writing down formulas, and trying to draw diagrams…if I can't remember, then I'm just trying to write it down and I'll try to figure it out later," and *Personalizing* information that involved rewording, e.g. "…putting what a lecturer is saying into my own words," or creating visualizations of the materials and ideas provided by teachers and instructors. Students stated clearly that 'Accumulating' was a key and necessary component of understanding physics; a precursor to applying and making meaning. However, they were unanimous that Accumulating, by itself, constituted a lower, subordinate level of understanding than applying and making meaning. Hence it is placed in a lower area in the outcome space. In what follows, the four other, superordinate conceptions are briefly explained.

Figure 1. The Outcome Space Representing Pre-service Physics Teachers' Conceptions of Understanding Physics.-



Feeling

The participants said that what it means to understand physics was to experience a feeling; a positive emotional response. Two sub-categories were identified: A feeling of *Personal Relevance* referring to when students saw physics as directly relatable to their lives, as exemplified by comments such as, "I like being able to look at things around me and know how they work…it's just fun," and a *Feeling of Knowing*, which meant that they could understand the material intuitively. This is exemplified by students' comments such as, "understanding physics

means it kind of (sic) just makes sense…an intuitive thing." Scholarship on feelings of knowing is highly visible in the literature, especially that which is related to metacognition (e.g., Efklides, 2006). Further, the importance of emotions for learning and understanding science is gaining increasing attention (e.g., Bellocchi & Ritchie, 2015).

Applying

The participants said that what it means to understand physics was to apply the physics one knows. Two sub-categories were identified: *Applying Knowledge* as using knowledge to solve problems and pass exams, as exemplified by comments such as, "I know I understand if I can do the questions,' and applying knowledge in the pursuit of *Inquiring* as being able to inquire and think critically about information and ask research questions in the field of physics, as exemplified by comments such as, "If I understand physics I can…develop my own procedure that makes sense…set up my own problem [to investigate] as thoroughly as I can." The sub-category of applying knowledge has been reported in previous studies (e.g., Irving & Sayre 2012; Lukie, 2021; Waterhouse & Prosser 2000). The second sub-category of *Inquiring* has not previously been reported to this researcher's knowledge.

Making Meaning

The participants said that what it means to understand Physics was to make meaning. Three sub-categories were identified: *Connecting Ideas* that involves seeing connections between physics concepts and ideas as exemplified by comments such as, "understanding involves…seeing how what we're learning fits into what I already know about a topic," *Seeing the 'Big Picture'* as being able to see physics as a field of study that can be connected to everyday life, often through the lens of mathematics and other areas of science, for example, "I see a car drive down the street, and I think of all the moving parts, and the mechanical engineering, and the thermodynamics…that's the basis of what physics is," and *Synthesizing*, as being able to deconstruct, reconstruct and revise concepts in potentially new ways, as suggested for example in, "[understanding physics is] seeking and finding patterns and logical structures in the world…mathematics is the main tool used to do that…[it's about] finding out how 'puzzle pieces' like, for example, energy, kilometres, hours, and formulas, fit together." To this researcher's knowledge, this subtle distinction between categories of making meaning has not previously been reported.

Communicating

The participants said that what it means to understand Physics was to communicate what one knows with others. Two sub-categories were identified: *Explaining*, meaning being able to explain physics to someone else, for example, "…being able to explain a difficult concept to somebody in layman's (sic) terms," and *Teaching*, meaning communicating with the intention of facilitating learning, for example being able to, "…tutor at university…to teach physics to somebody." The distinction between explaining and teaching is consistent that noted in past studies (e.g., Lukie, 2021; Irving & Sayre, 2012, Waterhouse & Prosser, 2000).

Conclusion And Implications

The significance of these findings relates to considering the everyday classroom event of a physics teacher asking their students, "Do you understand?" When they ask this question, what is it that are they really asking? Further, do teacher/s and students share similar epistemic positions on what it means to understand physics? The findings of this research suggest that a variety of conceptions of what it means to understand physics are possible for pre-service physics

teachers. Lukie (2021) reported similar variations between high school physics students and between high school physics teachers. The conceptions identified in this paper can be used, and are being used by this researcher, for initiating discussions with pre-service and practicing science teachers about what it means for individuals to understand physics. The outcome space shown in Figure 1 can be and is being used as a template for structuring such discussions. Further phenomenographic studies across science subject specialisms with pre-service and practicing teachers is required to expand the literature and potential use of such findings across teacher education.

Acknowledgement

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Fostering An Understanding Of The Significance Of Insect Care In Pre-Service Teacher Training

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This study investigates the effectiveness of a teaching intervention designed to enhance pre-service teachers' understanding of "thinking from the animal's perspective" in Living Environment Studies. A six-session intervention was integrated into a Living Environment Studies course for 24 pre-service teachers at a private women's university in Japan. Through discussions, lesson planning, and reflective activities focused on insect care, they explored the pedagogical value of perspective-taking in animal care. Post-intervention data from questionnaires and lesson plan analyses indicated that 83.3% of the pre-service teachers understood the importance of perspective-taking, with 66.7% linking it to fostering respect for life. Findings suggest that structured interventions can effectively equip pre-service teachers with strategies to cultivate empathy and a biocentric worldview in the children they will teach. Future research should explore integrating the coexistence of nature and humans and strengthening connections between Living Environment Studies and science education to enhance holistic animal care.

Keywords: Living Environment Studies, Insect Care, Thinking from the Animal's Perspective

Introduction

Living Environment Studies And The Educational Significance Of Animal Care

Animal care has been an integral part of Japanese primary education since the Meiji era. Initially rooted in science education, it has since become one of the core learning activities within Living Environment Studies (LES), as noted by Saito and Yoshimura (2023). This subject was established following the revision of the national curriculum guidelines in 1989 and fully implemented in primary schools in 1992 as part of Japan's educational reform. Taught in the first and second grades, LES helps children learn how to navigate their daily lives and grow through direct, hands-on experiences with people, their community, and the natural world. By exploring these connections, children begin to understand their place in the world and learn to interact responsibly with others and the natural environment. A primary goal of LES is to help children realize that nature is a vital part of their own lives. It encourages them to reflect independently on how humans and the environment can coexist harmoniously. In this way, the subject builds a foundation for a lifetime of harmony with the world. Within these lessons, caring for animals is especially important; it helps children develop a meaningful connection with other living beings, reflect on animal–human relationships, and cultivate empathy and respect for all life. The current national curriculum guidelines emphasize that animal care should involve observation and interaction that enable children to understand animals' needs and perspectives (MEXT, 2018).

This educational orientation is consistent with the natural tendencies of humans to understand and respond to animals, as indicated by psychological research. Fujisaki (2002) reported that humans naturally perceive emotions in animals and adjust their interactions accordingly, while Fujisaki (2004) emphasized that this ability is present from early development. Yamada (2012) noted that attributing emotions to animals is a general human characteristic. However, previous studies in LES have indicated that merely providing opportunities for children to interact with animals is insufficient for learning, and that structured learning experiences are necessary to help children shift from a human-centred perspective toward an understanding that incorporates animals' natural habitats, life processes, and ecological contexts (Onodera & Fujii, 2023).

Educational Value Of Insect Care In Living Environment Studies

When focusing on the types of animals kept in Japanese primary schools, recent studies indicate a clear shift in school-based animal care practices. The keeping of birds and mammals such as chickens and rabbits has declined due to concerns about infectious diseases and management burdens, whereas the keeping of relatively low-maintenance animals, including fish, amphibians, and insects, has increased (Nakajima, 2021). Among these animals, insects occupy a particularly significant position in LES. Insects are regarded as one of the most accessible materials through which children can experience and feel connected to nature in their everyday lives (Yamashita & Shuto, 2008). Previous research has demonstrated that even insects that children tend to find less appealing, such as crickets, can become objects of care and concern through sustained rearing and observation, leading to changes in children's perceptions and the development of attitudes that value and protect living beings (Saeki & Tsuchiya, 2012). Furthermore, the Science Council of Japan (2011) has emphasized the educational value of insects as school teaching materials, highlighting their manageable size, ease of rearing, species diversity, and suitability for learning about ecological roles and life processes. Because of these characteristics, insects serve as engaging hands-on examples of how life and ecosystems work, reinforcing why they are so highly recommended for school activities.

Given these characteristics and current educational contexts, insect care represents a particularly appropriate and meaningful focus for examining how children can be guided to think from the animal's perspective within animal care in LES.

Challenges In Teacher Education For Perspective-Taking In Animal Care

In classroom practice, facilitating this shift requires teachers to intentionally design learning situations that encourage children to think from the animal's perspective. Such situations may include activities in which children imagine animals' living environments, compare natural habitats with rearing cases, and reflect on how human actions influence animals' lives. Through these processes, children can begin to connect emotional engagement with cognitive understanding, thereby forming foundational perspectives related to respect for life and coexistence between nature and humans. Despite the recognized importance of these pedagogical approaches, existing research on teacher education for animal care in LES has largely focused on technical and managerial aspects, such as appropriate species selection and daily care routines (Miyazono & Miyagawa, 2012; Suzuki, 2006). While these studies provide valuable practical guidance, they have paid limited attention to how teachers can support children in thinking from the animal's perspective and linking such perspective-taking to ethical attitudes, including empathy and respect for living beings. Moreover, although research on teacher education in LES has accumulated since the subject's introduction, much of this work has emphasized understanding the subject's philosophy or improving general lesson design skills. As a result, there remains a notable lack of empirical studies examining how pre-service teachers learn to design animal care lessons that intentionally cultivate children's ability to consider animals' perspectives as a foundation for humane and responsible relationships with animals.

Purpose Of The Study

This gap in teacher training highlights the need for interventions specifically designed to enhance pre-service teachers' understanding of the importance of "thinking from the animal's perspective" in animal care. Accordingly, this study aims to investigate the effectiveness of such a teaching intervention implemented within a mandatory LES course for pre-service teachers. By developing and implementing this intervention, the study examines whether it can promote a deeper understanding of this concept and better equip future educators to foster empathy and

respect for animals in the children they will teach, thereby contributing to more comprehensive and compassionate animal care practices in Japanese primary schools.

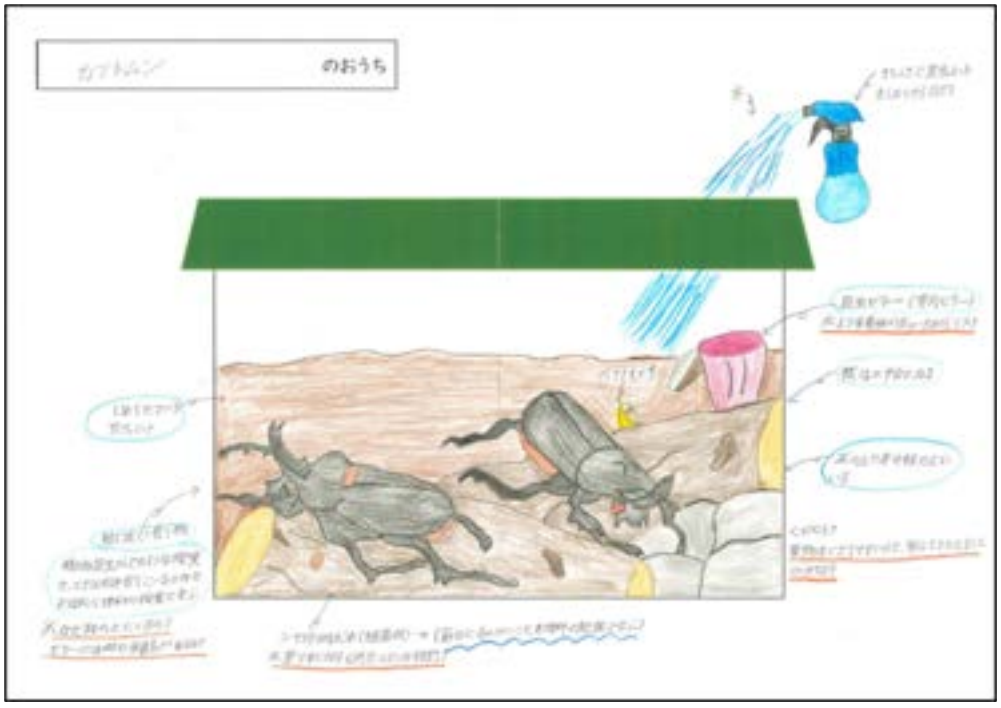
Method

Participants

The participants in this study were 24 second-year undergraduate pre-service teachers enrolled in a mandatory LES course at the faculty of education of a private women's university in Japan. The course constituted a core component of their pre-service teacher education program for obtaining primary school teaching certification. Before taking part in this study, they had already completed their foundational coursework in LES. Specifically, they studied the national curriculum standards issued by the Japanese Ministry of Education (MEXT), which are known as the Course of Study. This ensured that they were generally familiar with the government's official goals, core content, and the specific learning objectives required for primary schools across Japan. In addition to theoretical instruction, they engaged in experiential learning activities that mirrored those undertaken by primary school children, allowing them to examine LES from both learner and teacher perspectives. The course also addressed the continuity between LES and the rest of the curriculum. It emphasized how LES serves as an essential bridge to more specialized subjects including science and social studies, which children begin to study in the third grade.

Prior to the intervention, they had engaged in learning activities related to animal care. As part of this learning, they participated in an activity in which they designed a "home for insects" (Figure 1), focusing primarily on identifying and arranging the elements necessary for maintaining an appropriate rearing environment. This activity encouraged pre-service teachers to consider basic requirements for insect care, such as shelter and materials, from the perspective of preparing a suitable living space. However, these prior learning experiences provided limited opportunities for them to explicitly reconsider animal care from the animal's perspective or to examine how such perspective-taking could be intentionally integrated into lesson goals and instructional structures. Therefore, the instructional intervention in this study was designed to build upon pre-service teachers' existing knowledge of LES and animal care, while explicitly addressing this pedagogical gap by focusing on the educational significance of "thinking from the animal's perspective" and its incorporation into lesson design.

Figure 1. Worksheet used in the pre-intervention "home for insects" activity.



This study was reviewed and approved by the ethics committee of the university at which the author was affiliated at the time of data collection. Participation was voluntary, and informed consent was obtained from all pre-service teachers. They were informed that their decision to participate or not would not affect their course evaluation, and all data were anonymized and used solely for research purposes.

Intervention Lessons

A six-session intervention was designed to enhance pre-service teachers' understanding of the importance of “thinking from the animal's perspective” in animal care practice. The intervention was integrated into a 15-session LES course and focused on insect care as a concrete context for examining this concept. The intervention combined short lectures, guided discussions, and lesson design activities to support pre-service teachers in linking theoretical perspectives with practical lesson planning. An overview of the six intervention sessions is presented in Table 1.

In Sessions 10 and 11, pre-service teachers were introduced to the concept of “thinking from the insect’s perspective” through research findings on lower primary school children’s perceptions of insects and participated in facilitated discussions on its ethical and educational significance. In Sessions 12 and 13, pre-service teachers developed LES lesson plans on animal care, with explicit instructions to incorporate opportunities for children to consider insects’ perspectives within learning objectives, activities, and worksheets. Sessions 14 and 15 focused on peer review, revision, and reflection, enabling pre-service teachers to critically examine how effectively their lesson designs embodied the intended pedagogical focus.

Table 1. Intervention Lessons-

Session	Session Content
10	Introduction to the concept of "*thinking from the insect's perspective*" and its relevance to LES. This included a presentation of research findings regarding lower primary school children's perceptions of insects and their perspectives.
11	Facilitated discussion on the significance of incorporating "thinking from the animal's perspective" in animal care, prompting pre-service teachers to consider the ethical implications and potential benefits.
12-13	Pre-service teachers developed LES lesson plans focusing on animal care with an emphasis on "thinking from the animal's perspective". This included the design and creation of accompanying worksheets for primary school children to encourage engagement with the concept.
14	Peer review and constructive feedback sessions on the developed lesson plans and worksheets. Pre-service teachers revised and refined their teaching materials based on this feedback.
15	Pre-service teachers presented their final lesson plans and worksheets. A facilitated group discussion followed, focusing on the learning outcomes of the intervention, challenges encountered in the lesson planning process, and the overall significance of "thinking from the animal's perspective" in animal care.

Data Collection And Analysis

To evaluate the effectiveness of the instructional intervention in promoting pre-service teachers’ understanding of "thinking from the animal’s perspective," a post-intervention questionnaire was administered in July 2023. This took place following a 15-session LES course that incorporated a targeted six-session intervention. The questionnaire was designed to capture a comprehensive view of how pre-service teachers understood lesson design through a single open-ended question.

They were asked to describe, in bullet points, their primary takeaways regarding animal care lessons and the underlying rationale for their views. This single integrative prompt encouraged them to articulate their learning in their own words without being influenced by leading terminology. To safeguard the internal validity of the study, specific concepts such as "thinking from the animal's perspective" were not explicitly presented in the question. This design allowed for an examination of whether such ideas had been inductively internalized and prioritized by pre-service teachers.

The primary dataset consisted of the free-response text obtained from these questionnaires. To enable a more careful interpretation and bolster construct validity, the study employed data triangulation by analysing lesson plans and worksheets created during the intervention alongside the questionnaire responses. This cross-referencing served to verify whether the understandings expressed in written reflections were consistently reflected in pre-service teachers' actual lesson designs and learning activities. The qualitative analysis utilized a process of inductive coding, beginning with an exhaustive reading of the data to identify initial themes grounded in the pre-service teachers' own language. Through the method of constant comparison, these codes were iteratively tested against the entire dataset to ensure categorical consistency.

To mitigate researcher bias and achieve interpretive rigor, codes were refined into overarching themes over multiple rounds of review until thematic saturation was reached. Each theme was corroborated by representative excerpts to provide a clear evidence trail, ensuring the results remained firmly anchored in the raw data and demonstrated the plausibility of the emerging findings.

Findings

Learning Processes During The Intervention Lessons

During Sessions 10 to 15, gradual developments were observed in pre-service teachers' understanding of animal care, particularly regarding the importance of thinking from the insect's perspective, as reflected in their discussions, lesson planning processes, and reflective activities conducted during the intervention lessons.

Session 10 focused on establishing the goals of animal care activities in LES and introducing research findings on how children perceive the feelings of reared insects. Through individual worksheet writing and peer discussions, pre-service teachers articulated various reasons for the importance of adopting an insect-centred perspective, including fostering respect for life, helping children recognize their own anthropocentric assumptions, and promoting coexistence with other living beings. Overall, they came to view the cultivation of an insect-centred perspective as essential for respecting life and living together with insects in LES.

In Session 11, discussions centred on how lessons and activities could support a shift from human-centred to insect-centred thinking among children. Pre-service teachers proposed experiential activities such as role-playing insects confined in rearing cases or imagining changes to their own school environment and applying those feelings to insects. Notably, some who initially believed that simple observation was sufficient to foster perspective-taking reconsidered their views after listening to peers and began to emphasize the importance of embodied and expressive activities, such as dramatization, to support deeper understanding.

During Sessions 12 and 13, pre-service teachers developed lesson plans for the first time. Many plans set learning objectives related to imagining insects' feelings and designing appropriate rearing environments. The plans frequently incorporated experiential learning methods valued in LES, including simulated environments, role-play, and prediction activities. By creating

worksheets and anticipating children's responses, they repeatedly revised their lesson plans, reflecting on the alignment between learning goals, activities, and the intended perspective-taking.

In the final sessions (14 and 15), pre-service teachers evaluated and presented their lesson plans and reflected on the broader educational significance of animal care. Discussions highlighted the necessity of teachers intentionally designing activities that prompt children to think from an insect's perspective, while also cautioning against the imposition of fixed interpretations regarding an insect's feelings. They further explored the continuity between LES and science education, noting that the perspectives and skills cultivated through insect care, such as comparison, prediction, and respect for living environments, could be transferred to later science learning. These reflections indicate that pre-service teachers not only deepened their understanding of perspective-taking but also began to situate animal care within broader educational goals, including coexistence between nature and humans.

Analysis Of Questionnaires

The following excerpts (Table 2) from the questionnaires further illustrate pre-service teachers' understanding of the significance of "thinking from the animal's perspective" in animal care education. The qualitative analysis focused on identifying recurring ideas and patterns across pre-service teachers' free-response answers through repeated reading and comparison of responses.

Table 2. Emerging Themes from the Questionnaire Analysis

Theme	Example Quotes
Empathy and Perspective-Taking	• "It is crucial to design lessons that enable children to consider the needs of animals from the animal's perspective." • "It is important to encourage children to step into the shoes of animals." • "Through animal care activities, children can begin to think from the standpoint of living beings different from themselves." • "In LES, it is important to engage with various feelings, including those of oneself, others, and animals, without assuming a single correct answer."
Recognizing the Value of Life	• "It is also crucial to help children understand that animals, like humans, have lives that deserve to be valued and protected." • "I believe it is important for children to understand that animals, like humans, have lives and must be treated with care." • "By learning about the preciousness of life, children's attitudes toward animals may change."
Shifting from an Anthropocentric to a Biocentric Perspective	• "This can lead to a more life-centred and ecological perspective, allowing children to empathize not only with animals but with all living beings." • "This can help them shift from a human-centred viewpoint to an animal-centred viewpoint, leading to a deeper understanding of the value of life." • "By considering animals' feelings from multiple perspectives, children can shift from self-centred thinking to a life-centred way of thinking." • "Children need to recognize that animals play roles in nature and that these roles are connected to human life."
Fostering Responsible Behaviour	• "They may become more careful in their handling of animals and more likely to return them to their natural habitats after observation." • "Children may begin to handle animals more gently and return insects to their original environments after observation."

	• "Understanding the differences between natural environments and rearing cases can encourage children to act responsibly toward animals." • "It is important to care for animals responsibly by providing environments suited to their specific needs."

Analysis of the post-intervention questionnaires indicated that 83.3% (20 out of 24) of the pre-service teachers explicitly stated that incorporating "thinking from the animal's perspective" was crucial in LES animal care lessons. Further analysis of these 20 responses revealed that the majority (66.7%, or 16 pre-service teachers) associated this approach with raising children's awareness of life and fostering an attitude of respect for all living beings. They highlighted that encouraging children to consider the animal's perspective could lead to a deeper understanding of the value of life, promoting a shift from an anthropocentric viewpoint to a more biocentric perspective. The percentages reported here are used to indicate the relative prevalence of these themes among pre-service teachers and to complement the qualitative interpretation, rather than to provide statistical generalization. This suggests that the intervention successfully enabled pre-service teachers to understand the pedagogical value of "thinking from the animal's perspective" within LES.

Reflection in Lesson Plans

This understanding was further reflected in the lesson plans developed by the pre-service teachers. Many of these plans incorporated activities specifically designed to encourage children to empathize with animals. These lesson plans were examined to explore how the understandings expressed in the questionnaire responses were translated into concrete instructional ideas, with attention to features that appeared across multiple pre-service teachers' plans. Examples include having children enter a cardboard box designed to represent a rearing case to encourage them to imagine the feelings of an insect within, and role-playing activities where children take on the roles of both the "carer" (human) and the "cared for" (insect) to promote a deeper understanding of both perspectives. These findings demonstrate that the intervention was effective in not only enhancing pre-service teachers' theoretical understanding of "thinking from the animal's perspective" but also in equipping them with practical strategies to incorporate this approach into their future teaching. The emphasis on empathy and respect for life aligns with the broader aims of LES and reflects a growing recognition of the importance of fostering these values in primary education.

Discussion

Implications Of Key Findings

This research aimed to develop and implement a teaching intervention within a mandatory "Living Environment Studies" course for pre-service teachers to enhance their understanding of the significance of "thinking from the animal's perspective" in animal care. The findings suggest that the intervention was successful in achieving this aim. The majority of the pre-service teachers (83.3%) understood the importance of incorporating "thinking from the animal's perspective" in LES animal care lessons. Furthermore, most of them (66.7%) understood this pedagogical approach as a means to cultivate children's awareness of life and foster an attitude of respect for all living beings.

This positive outcome can be attributed to the design of the intervention, which provided opportunities for pre-service teachers to actively engage with the concept. By developing lesson plans and discussing the rationale behind "thinking from the animal's perspective," they were able to grapple with key questions, such as:

- What are the core goals of animal care education in LES?
- What does it mean to think from an animal's perspective?
- How can this approach be effectively incorporated into LES lessons?

This process of active engagement and reflection appears to have been crucial in deepening pre-service teachers understanding of the significance of this pedagogical approach. While previous studies in LES have highlighted the importance of children's experiential learning with animals, the present study extends this line of research by demonstrating how pre-service teachers can be supported in intentionally designing animal care lessons that foreground animals' perspectives as an educational goal. The intervention successfully highlighted the potential of "thinking from the animal's perspective" to not only enhance children's understanding of animal care but also to foster broader values such as empathy, respect for life, and a biocentric worldview.

Future Directions

Building on the findings and limitations of this study, two key areas for future development were identified:

1. Incorporating the concept of coexistence between nature and humans: While this study focused on fostering empathy towards animals, it is important to expand this concept to encompass a broader understanding of the interconnectedness between humans, animals, and the natural world (Matsumoto & Noda, 2009). Future interventions could explore ways to incorporate this concept of coexistence into LES animal care lessons, thereby encouraging pre-service teachers to consider the relationship between wildlife and humans, as well as the impact of human actions on the environment.
2. Exploring the connection between animal care in LES and science education: This study primarily focused on the role of animal care within LES. However, the values of respecting life and understanding living beings are also central to science education. Future interventions could explore the connection between animal care in LES and science, helping pre-service teachers design learning experiences that build a foundation for future scientific exploration while fostering ethical considerations regarding animals and the natural world.

By addressing these areas for future development, this research can contribute to more holistic and effective animal care in Japanese primary schools, fostering in children a deep understanding of and respect for animals and the environment. These efforts may also help pre-service teachers translate the pedagogical principles of LES into broader educational practices.

Limitations

This study has several limitations that should be considered when interpreting the findings. First, the pre-service teachers were drawn from a single private women's university in Japan, and the sample size was relatively small. Therefore, the findings cannot be readily generalized to all pre-service teachers or teacher education contexts. Second, the study relied primarily on self-reported data collected through a post-intervention questionnaire. Although the questionnaire was designed to encourage reflective and descriptive responses, the findings represent pre-service teachers' perceived learning rather than direct evidence of changes in teaching practice or long-term instructional outcomes. In addition, because no pre-intervention questionnaire was administered, it was not possible to quantitatively compare changes in pre-service teachers' understanding before and after the intervention. Third, all qualitative data were analysed by a single researcher. While a transparent and systematic analytic procedure was employed to enhance the trustworthiness of the analysis, alternative interpretations of the data may be possible.

Future studies could strengthen analytic rigor by involving multiple researchers or employing additional validation strategies, such as member checking or inter-rater discussion.

Finally, this study focused on pre-service teachers' understanding immediately following the completion of the course, including the instructional intervention. As a result, it did not examine how this understanding may develop over time or be enacted in actual classroom practice. Longitudinal research following pre-service teachers into their teaching careers would provide further insight into the sustained impact of learning to "think from the animal's perspective" in animal care.

Note

This paper is an expanded and revised version of part of the author's doctoral dissertation.

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Exploring The Attention Dimension Of Plant Awareness Through Drawing: From Stereotypes To Detailed Observations

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The construct 'plant awareness' emphasizes the importance of improving individuals' understanding, appreciation, and attention towards plants. This study explores the role of naturalistic drawing as a strategy to foster plant awareness, focusing on how pre-service teachers represent plants graphically without instruction. Both drawings and text notes were qualitatively analysed through the constant comparison method to classify them into conceptual categories (drawings) and based on information richness (text notes). We observed that students often struggle with representing the volume of plants -especially of those with dense foliage-, and that they tend to use stereotypes to represent plant parts and even whole plants, thus avoiding drawing difficulties. A main identified barrier was plant elements' overlapping, a trait that was not adequately captured in most drawings, which can be attributed to the natural evolution of graphic expression in most adult population lacking art training. Our findings support the idea that drawing is a useful strategy to promote observation and attention towards plants. However, instruction should focus on certain aspects that are particularly challenging for learners, so initial barriers can be overcome, and the observations of plant structures and traits can be refined.

Keywords: attention, naturalistic drawing, plant awareness, pre-service teachers

Introduction

The term 'plant blindness' (Wandersee & Schusler, 1999) describes how people tend to overlook plants. Since then, reversing this phenomenon has become a major goal of biological education. A recent conceptualization links 'plant awareness disparity' to a lack of attention, interest, positive attitudes, and knowledge about plants (Parsley, 2020). Pany et al. (2022) proposed using 'plant awareness' instead, emphasizing positive engagement. Recently, this theoretical construct was defined as "a multidimensional construct that reflects the level of an individuals' perception, understanding, and valuation of plants" (Dünser et al., 2024).

A key challenge in fostering plant awareness is enhancing individuals' attention to plants. One effective strategy to improve plant awareness could be promoting their observation through drawing (Eugenio-Gozalbo & Ortega-Cubero, 2022). Drawing deepens scientific understanding by stimulating intense observation and aiding effective data recording for subsequent study (Katz, 2017). Several theoretical frameworks address the role of drawing in learning. Dual coding theory states that integrating verbal and non-verbal information facilitates the construction of a coherent mental representation and recall (Paivio, 2014). The later theory of generative learning considers that drawing connects previous knowledge with new content, contributing to building mental models and enhancing understanding and recall (Fiorella & Mayer, 2016). However, drawing is a difficult task for many people, requiring spatial abilities that are hard to develop, and is time-consuming and cognitively demanding (Fiorella & Zhang, 2018).

Classical treatises on children's drawing emphasize that children tend to place each element in drawings in its own space, avoiding overlap. Objects in front of another are usually drawn next to, rather than partially overlapping, each other (Lowenfeld & Brittain, 2008; Martínez, 2004; Matthews, 2002). This trait persists in adults who have not advanced beyond the developmental

stages of childhood graphic language, which applies to most people. It leads to unconscious resistance, causing moments of creative block during demanding drawing exercises. To avoid this, most people use stereotypes—simple images as communicative symbols. The tree stereotype is particularly widespread, often depicted with a rectangular trunk supporting a rounded or fan-shaped canopy spread out on a single plane (Parini, 2002). Stereotypes are typically drawn with firm, inexpressive lines. Parini (2002) recommends using 'trembling, sharp, unpredictable, piercing, curved, or tortuous lines, or inventing one's own' to effectively depict different types of plants, emphasizing that these strokes 'are highly appealing for overcoming stereotypical representations' (p. 188).

In this research, we aimed at posing a naturalistic drawing exercise to pre-service teachers (PSTs) to be conducted without any artistical or biological instruction; to unveil the difficulties they faced in drawing and perceiving plant structure and traits. The exercise was conducted outdoors, with students free to choose any plant specimen, as we were also interested in such choices themselves.

Materials And Methods

The study involved third-year 39 PSTs in the compulsory subject 'Natural Sciences', of the Degree in Pre-School Education at the Faculty of Education of Soria (University of Valladolid, Spain). A teaching-learning sequence designed to promote plant awareness, published elsewhere (Eugenio-Gozalbo et al., 2024), combined artistic and scientific activities, both theoretical and practical, some conducted outdoors at an organic garden. The artistic part focused on observation-based drawing, particularly botanical illustration, to help students understand plant morphology, thus laying the foundation for effective learning of basic plant classification. One of the initial activities of such sequence was the naturalistic drawing exercise, whose results are presented here.

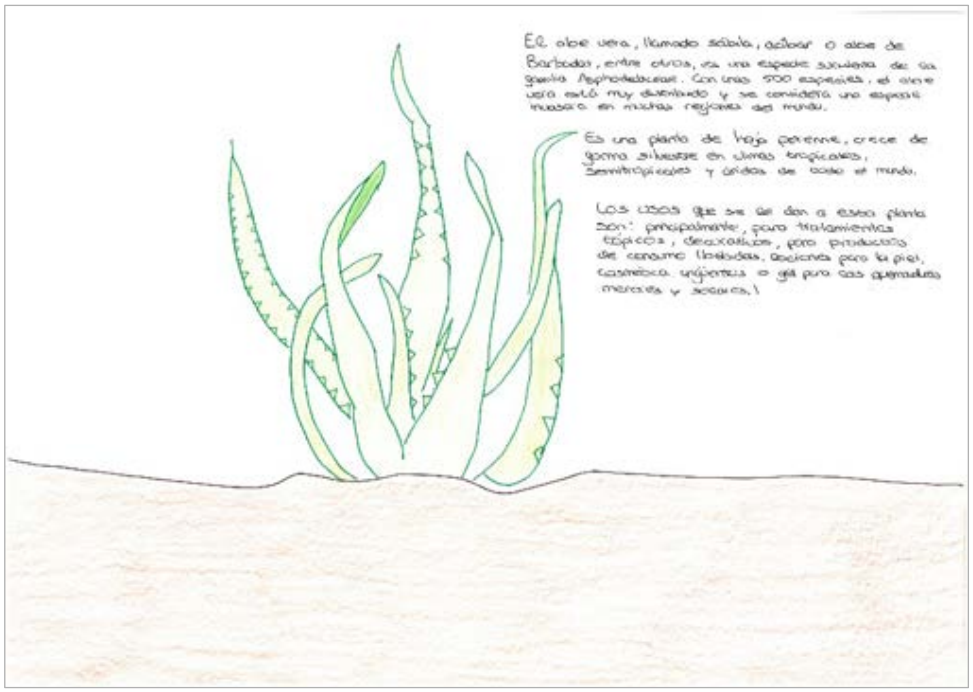
Students' drawings and text notes were qualitatively analysed by two researchers using Grounded Theory, through the constant comparison method. This approach involved systematically and iteratively examining the sample to identify emerging categories and subcategories of graphic representations, rather than using predefined classifications. The drawings were analysed together to detect recurring patterns and establish a more robust categorization. Text notes were categorised into three complexity levels (low, medium and high), based on the type and richness of information. The final categorization was reached through consensus between the researchers, who discussed all cases, particularly those with ambiguities.

Results

Drawing Analysis

Of the 39 drawings analysed, most students chose to depict trees (23), followed by herbaceous plants (12), and shrubs (4). A strong preference for flowering plants was observed, with 28 drawings featuring plants with flowers and only 11 without. Thus, trees were the plant form most frequently drawn, with 17 featuring flowers. Almond trees (Prunus dulcis) dominated this category, with 15 representations, while a pear tree (Pyrus communis) and a cherry tree (Prunus avium) were also included. The remaining six tree drawings depicted non-flowering species. Shrubs were less common, with an equal distribution between flowering and non-flowering species. Herbaceous plants accounted for 12 drawings, nine of which had flowers. Notably, three students selected Aloe vera, likely due to its simple appearance, though its thick, sculptural leaves posed unexpected challenges in conveying the sense of volume (Figure 1).

Figure 1. Example of an *Aloe vera* drawing with an inaccurate three-dimensional representation.



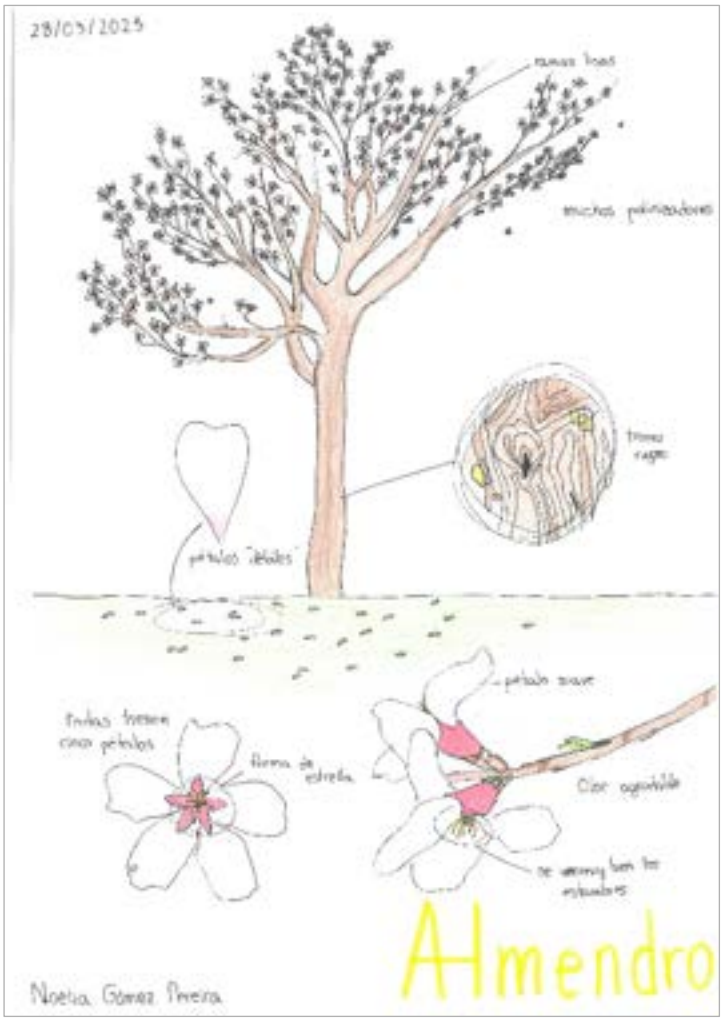
Students faced significant difficulties in tree representation, often lacking spatial awareness, resulting in flat, fan-like depictions with all elements displayed on the same plane (Figure 2). When drawing trunks, eight students failed to depict the gradual tapering of trunks, creating structures that widened and narrowed arbitrarily. In contrast, nine students correctly showed this transition, with six achieving a sense of volume. However, three avoided the challenge by focusing on small details like branches or saplings. Non-flowering trees exhibited similar issues, with half of the students' making distortions. For canopies, three students struggled to convey volume, instead outlining individual elements uniformly, thus avoiding overlapping. This approach resulted in rigid, repetitive patterns, reinforcing the flat, schematic nature of their drawings. Some added excessive leaves to conceal structural difficulties, as seen in an olive tree drawing. Few students included trunk textures, with only four drawings (poplar, olive, cherry, and almond trees) showing this detail. Similarly, leaf details were rare, appearing in a few cases (holm oak, two olive trees, one cherry, and one pear tree). Notably, the absence of leaves in almond trees at the time of observation likely influenced this.

A clear correlation between the quality of trunk and flower representations was observed. PSTs who depicted tree structures well also rendered flowers more accurately. The biggest challenge was capturing petal perspective, especially in non-frontal views, where some petals appear smaller. Six students successfully created recognizable flowers (five almond flowers, one pear flower), with most belonging to the group that achieved better tree representations. Common difficulties included simplification or exaggeration of petal shapes, the latter indicating effort despite inaccuracies. A strong example of expressive floral drawing was an almond flower drawing (Figure 3), where she used a loose, irregular stroke to capture petal fragility. When depicting flowers in tree canopies, students tended to repeat the same graphic symbol uniformly instead of creating texture, further reinforcing the fan-like canopy representation (see Figure 2).

Figure 2. Example of an almond tree (*Prunus dulcis*) representation in a single plane.



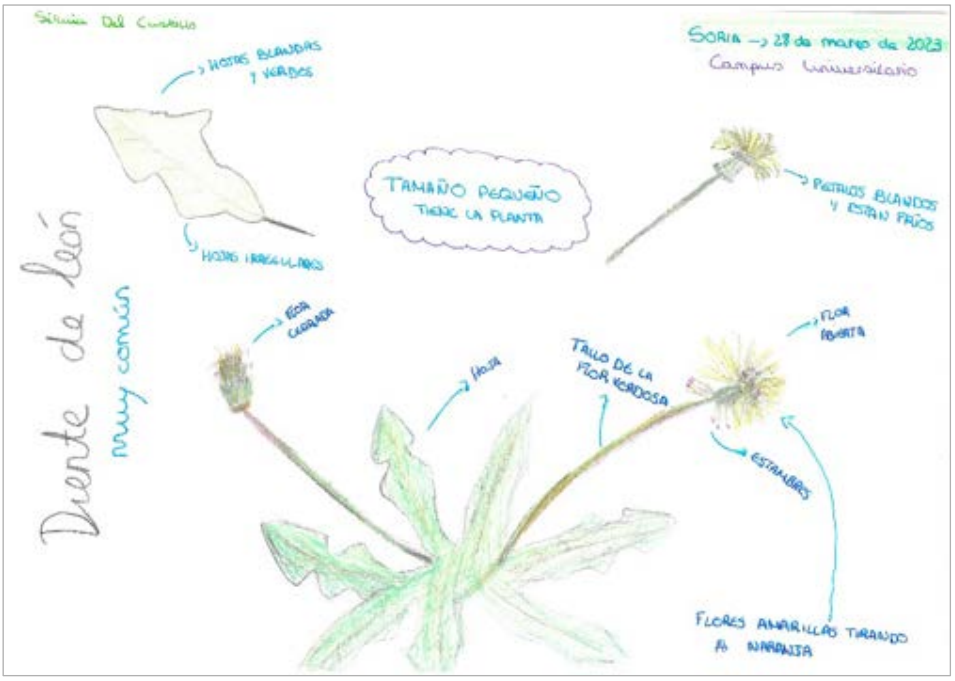
Figure 3. Example of an accurate representation of an almond flower (*Prunus dulcis*).



Students also encountered similar difficulties in representing volume with herbaceous plants, particularly tulips and *Aloe vera*, struggling to distinguish spatial relationships. In Asteraceae,

such as *Taraxacum* sp. and *Bellis perennis*, basal rosettes were depicted as undifferentiated masses rather than distinct leaves (Figure 4). Overall, students found it challenging to represent depth and spatial layering, indicating a broader struggle with volume perception in plant drawing.

Figure 4. Example of an inaccurate representation of a basal rosette.



Text Notes Analysis

Students' textual descriptions categorized at the low level (7 cases) typically reflected personal opinions or inaccurate observations, such as noting ‘much resistance’ or ‘irregular petals’ in the case of forget-me-not flowers (*Myosotis* sp.). This level also included information copied from the internet, such as descriptions of absent *Aloe vera* flowers. At the medium level (15 cases), students provided more concise and accurate labels. These included simple descriptions consisting of one or two adjectives (4 cases), such as “dark green stem,” or more specific, yet general, observations (11) like “petals flying in the wind” and “presence of many pollinators,” particularly for almond trees. While these descriptions lacked the richness found in higher-level texts, they still reflected the students' direct observations and were more consistent. The high level (10) included the most detailed and accurate descriptions. One student provided a long passage that described both the plant's context and its features, indicating a thorough awareness of the plant's environment. Other nine students used text notes that correspond to sensory details, such as the ‘lighter brown branches’ or ‘yellow stamens with anthers.’ In some cases, students acknowledged the limitations of their drawings and supplemented their observations with additional information.

Discussion And Conclusions

Students’ naturalistic drawings often focused on trees and flowering plants, likely influenced by their aesthetic appeal rather than other criteria. A minority chose specimens seemingly easier to draw, such as Aloe vera. In general, capturing the volume of plants proved challenging, as it was easier to depict the linear, less dense structure of herbaceous plants (with few leaves and one or more long stems, but not overlapping). This difficulty arises from the conflict between vegetal density, which is not a solid mass of leaves, and the tendency to avoid overlapping in graphic representation (Lowenfeld & Brittain, 2008; Martínez, 2004; Matthews, 2002). Thus, drawing details was easier than depicting the whole plant.

To address this challenge, it is important to provide students with strategies that focus on capturing the essence of plant forms, particularly volume and density. Emphasizing observation techniques that focus on textures, light, and shadow can help represent complex plant structures, including dense leaves or branches (Parini, 2002). Encouraging practice in both detailed and holistic representations will help them balance the intricate features of plants with their overall form. This approach encourages students to notice, reflect on, and appreciate plant morphology and complexity, ultimately improving plant awareness (Eugenio-Gozalbo et al., 2024).

Further discussion and research should address how drawing exercises can be effectively integrated into plant biology education to enhance students' observation skills. One key area of research is how to support students in moving beyond stereotypical representations of plants. Additionally, assessing the effectiveness of these educational strategies remains an important aspect for further development. The poster session will feature visual examples of the results, with an interactive component inviting participants to discuss these questions and exploring how drawing can serve as a valuable tool for improving plant awareness.

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Agile In Academia: Assessing Scrum's Potential For University Teaching

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This study explores the integration of the Scrum concept into university-level teacher training, specifically within a physics teaching internship preparatory course at Leibniz University Hannover. Originally developed for agile software development, Scrum promotes self-directed learning and iterative improvement, aligning well with modern educational approaches. The study investigates the effectiveness of Scrum in fostering pre-service teachers' competence development through a structured, team-based lesson planning process. A longitudinal study was conducted to examine changes in students' competence self-assessment. Data were collected at three points: before the preparatory course, after the course, and after the following school internship. Results indicate a significant increase in competence self-assessment during the course, attributed to the iterative, feedback-driven structure of Scrum. However, a stagnation or slight decline was observed during the school internship, likely due to real-world challenges in lesson implementation. Findings suggest that Scrum is a viable framework for teacher education, enhancing competence development through structured teamwork and reflective practice.

Keywords: Pre-Service Teacher Education, Professional Development, Learning Environments

Theoretical Framework

At the Physics Working Group at Leibniz University Hannover, students train to become secondary school teachers, with the module "Physics Teaching Internship" ("Fachpraktikum") playing a key role in their preparation. This module consists of a preparatory course at the university (1.5 hours per week over 14 weeks) and a five-week internship at grammar or vocational schools. The course aims to develop practical teaching competences through both subject-specific and pedagogical training. It encourages students to explore professional teaching approaches and to critically reflect on their actions based on educational research.

Previously, the preparatory course followed a traditional, lecturer-led format, focusing on lesson planning and execution. However, in the winter semester of 2022/2023, a paradigm shift toward more student-centred learning was implemented. Research indicates that self-directed learning enhances intrinsic motivation (Dignath & Büttner, 2008; Stone, Deci, & Ryan, 2009). This principle is integral to the Scrum methodology (Schwaber & Sutherland, 2020), which originates from agile software development, but is now used in many other areas. In the school sector, it was first adopted by Willy Wijnands in the Netherlands in 2011 as "eduScrum".

In the revised course format, students work in teams of three to five, with one member serving as team captain responsible for coordinating the group's workflow. Teams create lesson plans on assigned topics within three course sessions. They organize their tasks using a backlog, a tabular overview that lists specific work steps and tracks progress via mobile graphical elements. Completed lesson plans are uploaded to an online platform, where they undergo peer review. This review process provides critical feedback, which students use to refine their lesson plans. Regular team discussions allow members to assess their collaboration, identify strengths and weaknesses, and make improvements. This iterative approach ensures continuous enhancement of lesson plans and contributes to the development of a cohesive teaching unit.

The effectiveness of this Scrum implementation in academic teaching is investigated in an accompanying study, which examines its impact on student competences. The study already found that Scrum was well-suited for university-level education. Students particularly valued the small team structure and the lecturer's advisory role (Brockmann-Behnsen, 2024).

This report specifically examines the development of the students' competence self-assessment during the preparatory course and the internship. Competence, as a theoretical construct, is complex and lacks a universal definition (Weinert, 2001, p. 46). One relevant framework is "action competence", which includes problem-solving skills, critical thinking, social skills, and domain-specific strategies. In the school context, the German Conference of Ministers of Education and Cultural Affairs (Kultusministerkonferenz, 2004) defines key competence areas as *"teaching"* (instructional design, learning facilitation, differentiation, etc.), *"educating"* (values education, social development, conflict management, etc.), *"assessing"* (diagnostic assessment, performance evaluation, feedback, etc.) and *"innovating"* (professional development, reflective practice, school improvement, etc.). These domains are the focus of the current study on the effectiveness of Scrum-based learning in teacher training.

Research Questions

As the competence self-assessment is to be examined during the preparatory course and internship, a longitudinal study is appropriate. The research questions therefore focus on the developmental stages occurring throughout these two phases:

[Q1] How does the students' competence self-assessment represented by the above-mentioned areas 'teaching', 'educating', 'assessing' and 'innovating' change during the preparatory course?

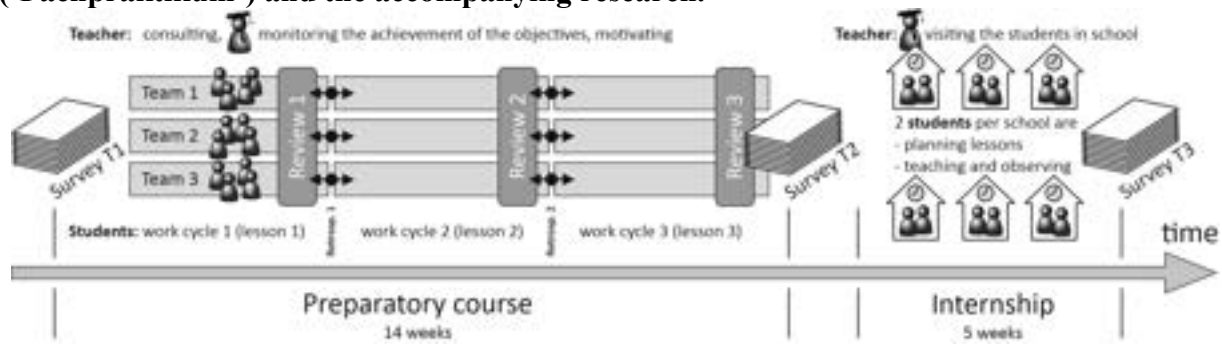
[Q2] How does the students' competence self-assessment change during the school internship?

Hypotheses:
It is to be expected that the competence self-assessment will improve during the preparatory course, as the iterative, incremental approach of the Scrum concept leads to a noticeable improvement in the lesson planning and corresponding feedback. During the block internship in the schools, on the other hand, students often experience that a good lesson plan does not necessarily lead to a good lesson. It can therefore be assumed that during this phase the competence self-assessment does not increase further or even decreases.

Methodology

Since the study is intended to examine the students' competence self-assessment in the course of the preparatory course and the internship, three measurement points were determined at which written surveys were conducted with the participants: at the beginning of the preparatory course (T1), between the preparatory course and the school internship (T2) and at the end of the internship (T3). Figure 1 provides an overview of the overall course of the module. In the preparatory course, the participants were introduced to the Scrum concept and then worked within the framework of this concept. The aim of this phase was to learn professional lesson planning. These skills were then applied during the block internship in a real school context. The scientific investigations reported in this article focus on effects of this innovative approach onto the students' competence self-assessment. Therefore, the research results presented here refer to the measurement points T1 vs. T2 and T2 vs. T3 respectively.

Figure 1: Overview of the courses in the "Physics Teaching Internship" module ('Fachpraktikum') and the accompanying research.



Instrument

The survey instrument consists of three questionnaires, which are used at the respective measurement times T1, T2 and T3 (see table 1). Scales from the KLiP study (Gröschner, & Schmitt, 2012; Gröschner, Schmitt, & Seidel, 2013) were used for all three measurement points to analyse the students' competence self-assessment. The items formulated there are based on the above-mentioned educational science standards of the German Conference of Ministers for Education. Six to eleven items each relate to the four areas of competence that are important for teacher professionalization: *"teaching"*, *"educating"*, *"assessing"* and *"innovating"*. The competence self-assessment is inquired by a seven-point Likert scale ("1" corresponds to "not at all competent", "7" corresponds to "fully competent"). The items are introduced by: "The teacher is capable of ..." ("Die Lehrperson kann …"). The Likert scale formulation and the initial sentence are intended to prevent the students' overestimation of their competences and tendencies towards socially desired response behaviour (see Gröschner et al., 2013, p. 81). In order to examine the development of the participants' competence self-assessment during the preparatory course (research question [Q1]) and during the block internship (research question [Q2]), the results from the questionnaires of the survey are used at points in time T1 vs. T2 and T2 vs. T3 respectively. The central tendencies of the two pairs of data sets were examined using Wilcoxon sign rank tests.

Sample

The sample consists of N = 39 students from courses in the summer semester 2023, winter semester 2023/2024, summer semester 2024 and winter semester 2024/2025; complete data was available from 32 participants (82% cohort utilization). The course participants were on average M = 24,13 (SD = 1,87) years old. The age ranges from 22 to 30 years. The reduced sample includes 24 males, 7 female and one with diverse gender. All of them are enrolled in the course of study for a teaching degree at grammar schools.

Results

Table 1 shows the median values (M) and interquartile ranges (IQR) of the students' competence self-assessments in the four areas "teaching", "educating", "assessing" and "innovating" at the three survey times. Cronbach's α was determined to examine the internal consistency of the scales. For the areas "teaching", "educating" and "assessing" the competence self-assessment increase is significant ($p < 0{,}001$) in between timepoints T1 and T2 with median increases of 1. Between timepoints T2 and T3 only the area of 'teaching' shows a significant increase in competence ($p < 0{,}01$).

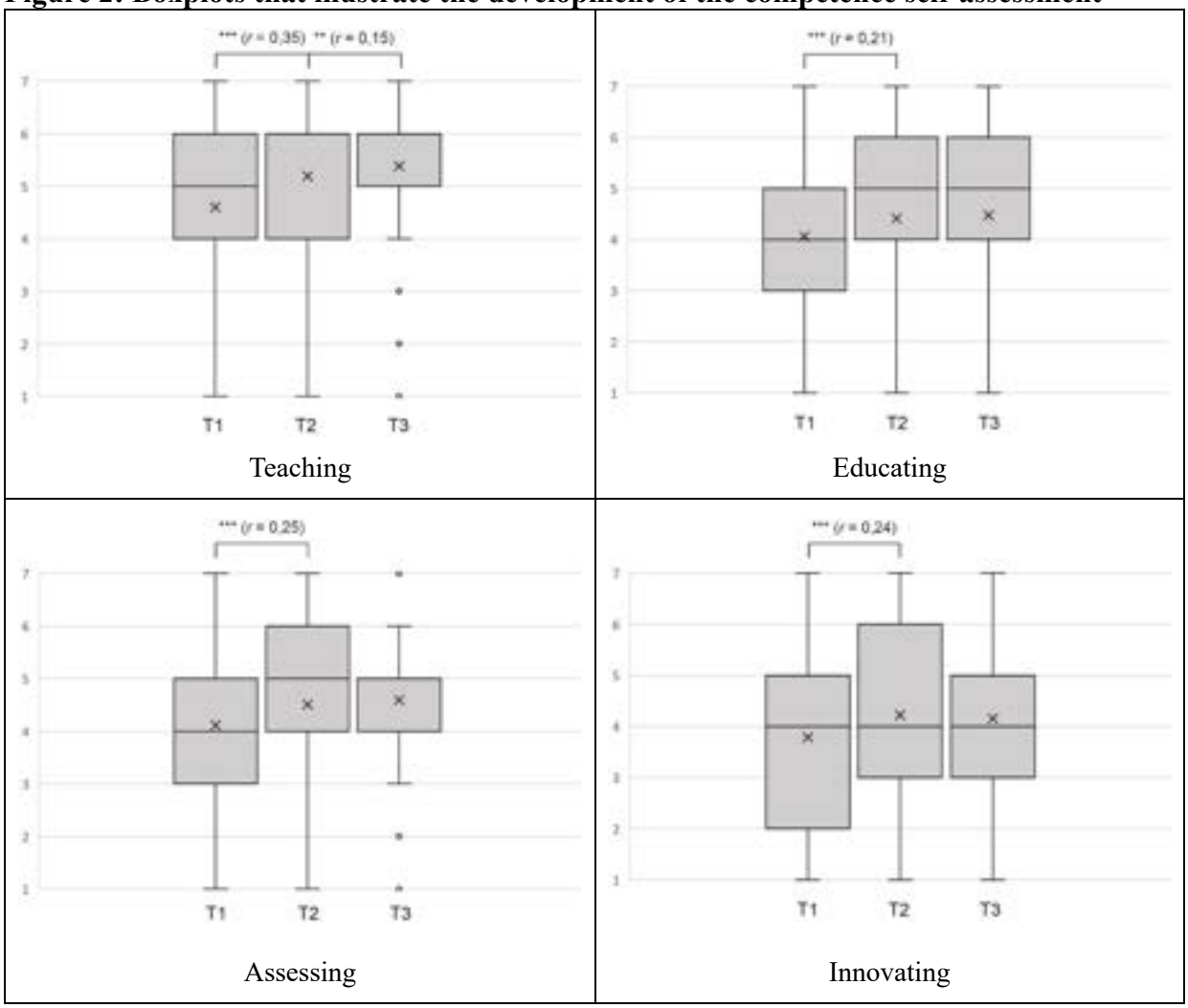
Figure 2 shows the distributions of the students' responses as box plots. The increase in self-assessments of competence between the time points T1 and T2 and the stagnation or decline

between the time points T2 and T3 can clearly be seen. The determination of the effect sizes shows small effects for all areas between the time points T1 and T2 (Pearson's r [0.21; 0.35]) and also a small effect for the 'Teaching' area between the time points T2 and T3 (r = 0.15).

		T1		T2		T3	
Scale	Items	*α*	*M (IQR)*	*α*	*M (IQR)*	*α*	*M (IQR)*
Teaching	11	0,82	5 (2)	0,85	6 (2)	0,86	6 (1)
Educating	9	0,76	4 (2)	0,89	5 (2)	0,81	5 (2)
Assessing	7	0,74	4 (2)	0,85	5 (2)	0,82	5 (1)
Innovating	6	0,81	4 (2,5)	0,78	4 (3)	0,87	4 (2)

Table 1: Results and statistical values for the competence self-assessment scales.

Figure 2: Boxplots that illustrate the development of the competence self-assessment



Discussion

Testing innovative concepts is of great importance for research in university teaching. The iterative and student-led approach of Scrum is a very innovative concept. It is therefore an important finding that this concept led to significant increases in the students' competence self-assessment in three of the four scales analysed during the preparatory course. This was to be expected, as the students experience themselves as very effective when working in small teams and generally receive a lot of praise and constructive feedback in the regular reviews. Due to the high frequency of the work loops, they also experience a rapid improvement in their lesson planning. This apparently also leads to an increase in self-perceived competence. It is interesting that the increase in competence self-assessment does not only refer to the area of *"teaching"*,

which is particularly addressed in the preparatory course, but is apparently also transferred to the areas of *"educating"* and *"assessing"*. It is unexpected that the preparatory seminar on the Scrum methodology does not have a significant impact on "innovation", as this methodology places particular emphasis on regular introspection and reflection with the aim of optimisation.

The stagnation or decline in the self-assessment of competences during the practical phase following the preparatory course is noteworthy. Here, the students are no longer in the familiar surroundings of their teams and the academic environment but have to implement their lesson plans into the reality of the school. They learn that not every lesson plan that is promising in theory will prove successful in everyday school life. This experience obviously manifests itself in a decline in self-assessment of competence. In this context, it is interesting to note that Gröschner et al. (2013), who developed the questionnaire used here to investigate the self-assessment of competences during a practical semester, came to different conclusions. There, the self-assessment of competence increases with the degree of perceived learning support during the practical phase. The practical phase described here does not extend over an entire semester, but only over a period of five weeks. For organisational reasons, it is also only possible to visit the students once during this time. It can be assumed that the learning support is therefore perceived as rather low. There is clear potential for improvement in this regard, particularly with respect to the duration of the practical phase. Empirical studies, such as those by Gröscher et al., demonstrate that an extended practical semester can be highly effective when accompanied by structured and high-quality supervision. In the study presented here, lesson plans were regularly reviewed and refined through systematic, collaborative critique within the preparatory seminar. Extending this iterative process into the practical phase would allow for continuous further development of instructional design. Such sustained optimisation of teaching practice is likely not only to enhance instructional quality but also to positively influence students' self-perceived teaching competence.

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Part 16 / Strand 16

In-Service Science Teacher Education And Professional Development

Co-editors: *Elia Tena & Pedro Reis*

Part 16 / Strand 16 In-Service Science Teacher Education And Professional Development

Continuing professional development of science teachers, including in-service science teacher education programmes and policies, teachers as lifelong learners, strategies and methods for teaching science, innovation and reform in professional development, evaluation of professional development practices, reflective practice, teachers as researchers, and action research.

Sub-themes:

1) Continuing Professional Development Strategies for Science Teachers
2) Reflective Practice and Teacher Research in Science Education
3) Evaluating the Impact of In-service Teacher Training
4) Lifelong Learning and Career Development for Science Teachers

Contents

Strand 16: In-service Science Teacher Education and Professional Development 1434

Section: Continuing Professional Development Strategies For Science Teachers..... 1436

Digital inequalities in the context of teaching and learning of science and technology in secondary school..... 1437

Adaptive Gamification in Primary Science Education: Teacher Implementation 1443

Developing sustainable professionalization programs for STEM teachers by systematically reflecting on transfer pathways..... 1449

Professional development in out-of-school learning environments to promote teachers' ICT skills – How can we scale-up our best practice examples?..... 1459

Understanding In-Service Stem Teacher Professional Development Needs: A Literature Review 1468

Aesthetic Learning Processes In Science Education – Cultivating Empathy And Curiosity For Nature In Primary And Middle School Science 1474

Empowering STEM Teacher Professional Development Through AI Integration 1483

Bridging The Gaps In STEAM Education: Voices Of Educators 1488

Section: Reflective Practice And Teacher Research In Science Education 1494

Building Knowledge Together: How Collaborative Professional Development Fostered New Learning Opportunities For Secondary Physics Teachers..... 1495

Development of Teacher Training Model that Transforms the Science Teacher Competencies 1503

Exploring Physics Teachers' Use Of Lab Through Actor-Network Theory..... 1515

Addressing Misconceptions Through Questioning: the Application of Teacher Knowledge in a Primary Science Lesson..... 1523

Section: Evaluating The Impact Of In-service Teacher Training..... 1528

Exploring the impact of a multidisciplinary sustainability course for teachers: analysis through greencomp 1529

Enhancing Teachers' Beliefs, Self-Efficacy and Professional Knowledge through In-Service Teacher Professional Development Programs on the Use of (Interactive) Experimental Videos 1535

Navigating Digital STEM Professional Development: Insights From Out-Of-School Labs .. 1545

Assessing The Impact Of Lesson Study-Based Professional Development On Spatial Skills Of Primary Students..... 1554

Shifting Teachers' Knowledge And Confidence For Engaging Students In Science Practices From A Program Designed By Scientists And Pedagogical Experts 1559

Section: Lifelong Learning And Career Development For Science Teachers 1567

Science Teacher Educators In Professional Learning Communities: Exploring The Possibilities Of Creating New Organizational Routines..... 1568

Fostering STEM Teacher Identity Development In Primary And Secondary Science Education 1572
Didactic Dimension Of The Professional Identity Of Tunisian Physics And Chemistry Teachers 1581

ESERA 2025 Copenhagen

Strand 16: In-Service Science Teacher Education And Professional Development

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Introduction

The papers gathered in strand 16 address one of the central challenges currently facing science education: how to support teachers' professional learning in a period marked simultaneously by ecological urgency, rapid digital transformation, and growing demands for more equitable, interdisciplinary and socially relevant science education. The ESERA 2025 conference themes of sustainability and digital advances are therefore not peripheral to this collection; they form a central axis around which many of the contributions are organised. Sustainability is approached not only as scientific content to be taught, but also as a multidimensional educational orientation involving values, systems thinking, future-oriented reasoning, responsible action, nature connectedness and socio-environmental engagement. Digital advances, in turn, are considered not merely as tools to be adopted, but as developments that reshape the conditions, practices and purposes of science teaching, raising questions of teacher competence, professional identity, equity, accessibility, ethical use, pedagogical quality and institutional support.

The strand "In-service Science Teacher Education and Professional Development" focuses on the continuing professional learning of science teachers and science teacher educators across different educational levels, institutional settings and national contexts. It encompasses in-service teacher education programmes and policies, teachers as lifelong learners, professional development models, innovation and reform in science teaching, reflective practice, teachers as researchers, lesson study, action research, professional learning communities, and the evaluation of professional development practices. At its core, the strand is concerned with how teachers learn, how they transform their knowledge, beliefs, practices and identities, and how professional development can be designed so that it is meaningful, sustainable and connected to the realities of classrooms, schools and wider educational systems.

Taken together, the contributions show a field that is moving beyond short, decontextualised training events towards richer, more situated forms of professional learning. Across the papers, professional development is frequently conceptualised as collaborative, inquiry-oriented, design-based and practice-embedded. Teachers are positioned not simply as recipients of expert knowledge, but as active interpreters, designers, facilitators, reflective practitioners and co-constructors of innovation. This is visible in studies centred on lesson study, professional learning communities, design-based research, co-design, out-of-school laboratories, teacher learning communities, classroom implementation cycles and reflective inquiry. The emphasis falls on the dynamic relationship between professional development design and teachers' actual possibilities for action in specific school, curricular, technological and cultural contexts.

Several major thematic clusters emerge across the strand. One concerns sustainability and socio-environmental education, including professional development for sustainability competences, climate-change education, nature connection, aesthetic engagement with the natural world, and interdisciplinary STEM or STEAM approaches to complex real-world problems. A second cluster addresses digitalisation and emerging technologies, including ICT-related professional

development, interactive experimental videos, adaptive gamification, artificial intelligence and ChatGPT-supported teacher learning, digital inequalities, and the use of digital tools in laboratory and inquiry contexts. A third cluster focuses on teacher knowledge, beliefs, self-efficacy, professional identity and competencies, showing how professional learning involves cognitive, affective, epistemic and practical dimensions. A fourth cluster examines organisational and systemic conditions for sustainable professional development, including transfer pathways, scaling-up, professional learning networks, institutional routines, resources, time, leadership, policy support and cross-institutional collaboration.

The most prevalent trend across the papers is the search for professional development models that are both pedagogically ambitious and practically viable. Many contributions recognise that teachers are expected to address complex and rapidly changing demands, but often do so under constraints of time, resources, curriculum structure, assessment regimes and uneven institutional support. Consequently, the question is no longer only what teachers need to learn, but how professional learning opportunities can be organised so that they are coherent, sustained, context-sensitive and capable of supporting actual classroom change. Another strong trend is the integration of content, pedagogy and technology, particularly through approaches aligned with TPACK and related frameworks. Digital innovation is treated as productive when it is connected to disciplinary learning, inquiry, experimentation, feedback, inclusion and student agency, rather than when it is used as an isolated technical add-on.

A further trend is the broadening of science teacher professional development towards interdisciplinarity and societal relevance. Integrated STEM and STEAM, sustainability education, climate education and real-world problem solving require teachers to cross disciplinary boundaries, work collaboratively, tolerate uncertainty and develop new professional identities. The papers also reveal a growing concern with equity and accessibility: digital inequalities, inclusive STEAM environments, access to technological infrastructure, and the need to avoid reinforcing existing divides all appear as important issues. Finally, there is a clear methodological tendency towards research designs that make professional learning processes visible, including qualitative case studies, mixed-methods evaluations, systematic reviews, design-based research, lesson study analysis, reflective journals, observations, interviews, surveys and studies linking teacher learning to student outcomes.

Within the wider field of science education research, this set of papers contributes to a more complex understanding of teacher professional development as a systemic, relational and transformative process. It reinforces the idea that improving science education depends not only on producing new curricula, technologies or resources, but on understanding the conditions under which teachers appropriate, adapt, question and sustain innovation. The strand also strengthens the connection between science teacher education research and current educational challenges: preparing learners for sustainability, supporting scientifically informed action, responding critically to digital transformation, and developing inclusive, practice-based and evidence-informed forms of professional learning. In this sense, the collection illustrates a mature and evolving field, attentive both to the micro-processes of teacher learning and to the broader institutional, technological and societal conditions that shape science education today.

Section: Continuing Professional Development Strategies For Science Teachers

ESERA 2025 Copenhagen

Digital Inequalities In The Context Of Teaching And Learning Of Science And Technology In Secondary School

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In Quebec, since the implementation of the Education Reform, the teaching and learning of science and technology (S&T) at the secondary level has raised several questions. Initially, developing the interdisciplinary component proved challenging, and adolescents' motivation towards this pairing of disciplines, despite concrete focus, has not improved. Additionally, the place of digital technology in the classroom can no longer be ignored, as digital inequalities negatively impact S&T teaching and learning. Furthermore, access to digital technology varies significantly between educational institutions.

In 2015, the Organisation for Economic Co-operation and Development came out in favor of access to digital technology in the school environment. Digital inequalities are then considered a complex problem arising from an authentic situation in the school environment, mobilizing different resources in an imperfectly predictable and difficult to break down function.

To describe the problem of digital inequalities in the school environment, a research initiative involving university researchers and school stakeholders was realised between 2022 and 2024. Led by a facilitator, a group was mobilized to address the problem of digital inequalities. This article explores the meeting dynamics (5 meetings) and the facilitator's role (convene, observe, reflect, act and harvest) in solution co-creation.

The facilitation role can be effectively undertaken by science teachers, enabling them to bridge digital gaps and enhance the teaching of science to secondary school students. This approach empowers educators to integrate interdisciplinary and technological elements into their pedagogy more effectively.

Keywords: Facilitation, U theory, digital inequalities

Introduction

The purpose of this text is to identify and describe the role of facilitator agents in the context of the activities of a co-creation group that is inspired by design thinking and is part of a living laboratory. Thus, participants from various fields, occupying different professional functions and expressing sometimes divergent opinions participate in the co-development of solutions to counter digital inequalities in science and technology (S&T) courses at the secondary level (12 to 17 years old). The approach used by the facilitator agent to support the participants and allow the expression of their perceptions of the situation is design thinking. One of the main challenges of the function of facilitator agents, during these meetings of the co-creation group lies in the ability to listen and be open to the expression of divergent opinions. The challenge of facilitating these meetings is to create an environment of trust and respect that encourages participants to express their thoughts and propose solutions that could produce tangible societal repercussions on digital inequalities in the school environment. During the meetings held, in person and remotely, a facilitator led the group's discussions. The role of this person proved to be important, which led the research team associated with the project to take an interest in their actions and posture. It is by taking these conditions into account that the team of researchers decided to look at the professional action of its facilitator agents to describe and validate their potential for the

co-development of solutions. A question also raises the interest of researchers: What is the role of facilitator agents in a co-creation group of a living laboratory in education? The general objective of the project is to establish a living laboratory for innovation in education (LaVIE) in order to co-create, with stakeholders and users, innovative solutions that promote the adaptation of educational and pedagogical practices to combat educational and digital inequalities exacerbated by the pandemic.

Indeed, although digital inequalities in the school context are recognized and manifest in the manner in which courses are delivered and learning is generated, particularly in S&T teaching where the abstract side of concepts is often dominant, the complexity of the situation precludes a single, simple solution to this problem. That is, the problem is one with no possible definitive resolution (Rittel and Webber, 1973).

Conceptual Framework

According to Stewart and Sampsa (2008), facilitation is defined as the provision of opportunities for various actors affected by a social problem. For them, these opportunities include the provision of information, the establishment of connections, and the allocation of resources. The purpose of these opportunities is to enable these actors to identify and implement remedies for the social problem. Johnson (2018) adds to this definition that the facilitator is a person whose responsibility in research is to help teams conduct and learn innovation work from ongoing projects, without however directing or managing the work themselves.

Facilitation emerged in the early 1960s in the United States. During this decade, there were major debates against the Vietnam War, racism and poverty (Gauthier, Bibaud & Roy-Baillargeon, 2011). Twenty years later, it is mainly returning in the environmental protection and sustainable development awareness movements (Doelle & Sinclair 2006). In this context, facilitation responds to a need for modifications and accommodations of social objectives.

"The term facilitation can be approached in two ways: either interchangeably with the notions of mediation, conciliation and consultation or comparatively with mediation and negotiation." (Gauthier et al., 2011) Facilitation is oriented towards prevention where the discussion methods are fair and open. It contributes through its logistics to the proper conduct of meetings. It promotes active listening and the identification of opportunities for consensus between participants (Dorcey and McDaniels, 2001). Through public debate, it helps to raise awareness among participants so that they can increase their involvement and better coordinate their actions with their community (Thomassian, 2009).

An important part of the facilitators' task is to guide participants toward an agreement by creating a climate of trust and transparency that is conducive to verbalizing needs, sharing information, and analysing all proposed options in order to identify and develop an integrated, equitable, and sustainable solution to the problem under study (Beuret 2006; Milburn 2006). The interactive dimension of facilitation involves seeking an agreement. It is directed toward transforming the conflict by establishing a dialogue between project participants. The interactive dimension also leads them to change their perceptions of the situation and develop an openness to negotiation. Facilitation thus contributes to improving collective understanding of the issues, empowering the parties, and managing emotions (de Carlo 2004a). Balancing emotions is achieved by setting limits on interactions between participants. Facilitation thus generates avenues for compromise or solutions on the relevance of the project in order to facilitate integration into its environment. Therefore, facilitation through its function with participants is oriented towards i) collective decision-making (de Carlo 2004a and 2004b; Kaufman 2009), ii) the ability to prevent conflicts, iii) the social acceptability of projects (Karjalainen & Järvikoski 2010; Peltonen & Sairinen 2010,

and iv) the manifestation of collective intelligence and social cohesion (Fortin, 2009; Kaufman 2009). In addition, being a facilitator agent implies understanding a problem in order to determine its limits and constraints (Glen, Suciu & Baughn 2014). This is manifested by the ability to frame and reframe the problematic situation from different angles, from microscopic and macroscopic levels, and this, at all stages of the targeted project. Framing is linked to the development of critical thinking. It consists of undoing the unconscious biases generated by life experiences, appropriating systems of thought, understanding the main ideas which guide the choices and opinions of the participants.

The objective of the meetings was twofold: first, to assist educational stakeholders and participants in comprehending the issue of digital inequalities in the school environment, with a particular focus on science and technology education, and second, to facilitate the conception and evaluation of innovative solutions.. The support or action of educational stakeholders in the face of digital inequalities constitutes a lever. Facilitators also prevent situations of tension by promoting interaction between the different stakeholders so that they produce common solutions while having initially expressed divergent interests and opinions (Dorcey and McDaniels 2001; de Carlo (2004a); Pereira, Drimie, Zgambo & Biggs (2020)) the primary responsibility of the facilitator lies in their ability to adequately interpret the meaning of the words of the different stakeholders so that it is understood by all and used as a basis in the development of a new social message.

Duhigg (2024) mentions that when a discussion group feels positively guided and respected by a facilitator, few participants are aware of the real influence it has on the evolution of their thinking and their membership in the group. The facilitator then plays an essential role in sharing thoughts and in the evolution of opinions on the situation of digital inequalities.

Design Thinking

Design thinking, centred on the human, requires taking a step back from actions in order to ensure an optimal understanding of the problem to be addressed by the participants, before focusing on the solutions to be explored. In addition, this approach implies, in its implementation, that the shared reflections take into account the experience of the participants. For Brown & Wyatt (2010) a research project conducted according to the design thinking approach is made up of several stages where each is linked to an objective, results and diagrams. Furthermore, these stages do not necessarily occur successively; they can coexist in their implementation.

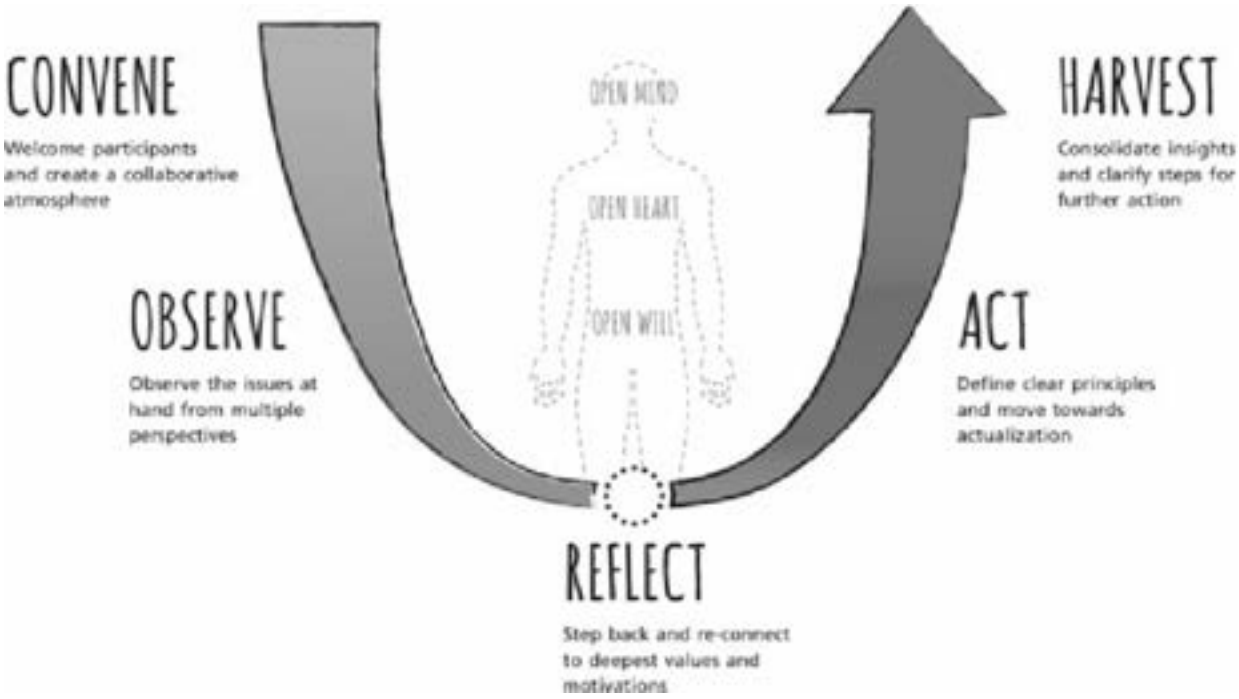
The design thinking model, as used for the project, is made up of two phases and six stages. The phases represent the problem space and the solution space. The steps in the problem space phase, for their part, require defining the problem, understanding it by consulting the people who experience and know it, and then, if necessary, redefining it more precisely. The subsequent step in the process is to envision multiple solutions, prototype them, make them tangible, and test them with the intended users. This method is called collaborative because all participants must be involved in the process.

Methodology

The authors Pearson et al. (2018) and Scharmer (2016, 2009) proposed a modelling of the change process through reflection and sharing of perceptions. The goal of this model is to present an evolving sequence of meetings (in workshops) in order to lead participants to design a common solution to improve a situation that has become socially difficult. Called the U theory, this model is used as a co-design tool. It is easy to understand for the facilitators and provides essential time for individual reflection followed by sharing. It thus marks the duration of the different stages of

the meetings. According to Pearson (2021), the stability and predictability of this framework contribute to facilitating the engagement of the participants. The U theory explicitly aims to open up spaces of possibilities.

Figure 1. Theory U The Theory U process of co-sensing and co-creating[1].



The application of the Pearson et al. model. (2018) can be summed up in five stages: a) the gathering (convene) where a climate of collaboration is created, b) the observation (observe) of the different facets of the problem to be solved, c) the reflection (reflect) on the values and principles inherent in the problem and the motivation of the actors to modify elements, d) the action (act) redefine the principles retained and update e) the harvest (harvest) clarification and consolidation of the possible stages to be put in place.

To analyse the meetings held between 2022 and 2024, based on these stages, their content was transcribed in verbatim form. A sequenced thematic analysis was applied to part of the verbatims (4 pages of verbatim from the first meeting) by the authors of the text. After this exercise conducted independently, an inter-judge validation meeting was held to consolidate the analysis grid. Subsequently, an author analysed all of the identified verbatims.

The Results

The facilitator's professional actions, including her invitation to engage in the discussion and her openness to diverse opinions, fostered an environment conducive to the expression of individual perspectives while respecting the divergent ideas of others. The quality of her facilitation made it possible to define the constitutive parameters of digital inequalities, information whose nature is linked to the professional status of the different participants and the relationship they have with the use of digital technology.

The U-model appeared operational and can be used as a tool for the expression and analysis of design thinking in the context of the living laboratory. The five stages of the U-model were

[1] Source: Pearson et al. (2018) as adapted from Scharmer (2009) Creative Commons Attribution 4.0 International

manifested. However, nuances must be made, particularly on the succession of stages in an iteration (back and forth) where several stages of the model are likely to manifest themselves during the same meeting. It should be mentioned that the different stages of the model are associated with reflections and the expression of these reflections. In addition, everyone has their own way of creating links between the comments made by the participants and the realities as they perceive them on digital inequalities in the school environment.

The facilitation role can be effectively undertaken by science teachers, enabling them to bridge digital gaps and enhance the teaching of science to secondary school students. This approach empowers educators to integrate interdisciplinary and technological elements into their pedagogy more effectively.

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Adaptive Gamification In Primary Science Education: Teacher Implementation

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Implementing adaptive gamification in science education, supported by teacher training, is vital to enhance students' engagement and learning. This study examined how teachers trained in a TPASK-based program integrated and utilized an adaptive gamification application in teaching science concepts related to the water cycle with 3rd-grade students. using observational checklists. This study examines the training of teachers regarding the use of an adaptive gamification application, in the teaching of science education concepts in elementary education. The main point of interest was collecting first-hand data on the degree of effective utilization and pedagogical integration of the adaptive gamification environment by in-service teachers. The data were collected through the use of observational checklists based on the TPASK dimensions after the implementation. Results revealed two teacher profiles based on TPASK proficiency and diverse application strategies. The findings highlight the potential of such practices in early and primary education and emphasize the need for teacher training to utilize adaptive learning digital application and ongoing support to address implementation challenges.

Keywords: Adaptive education, Teacher implementation, TPASK framework, motivational aspects, science education

Theoretical Framework

In recent years, due to new challenges and demands, education has been in a process of reconfiguration, especially after the coronavirus period (Shehaj, 2022). In general, the role of the teacher has changed over the years, as the teacher is now expected to provide strategic support to students to help them become self-directed learners (UNESCO, 2008). However, this requires the redefinition of teachers' professional skills (Torrance & Forde, 2017) and the enhancement of their training to enable and facilitate the development of essential skills such as collaboration, critical thinking, problem-solving, scientific and digital literacy in today's world (Dede, 2010; Torrance & Forde, 2017). Enabling students to acquire modern skills such as scientific and digital literacy requires teachers to use and/or create appropriate classroom scenarios that inspire, motivate, and engage students in learning (Mee et al., 2020). One of the current trends that is attracting the interest and attention of teachers and students alike is that of gamification (Statti & Torres, 2020).

Several researchers have focused on applying gamification in science education due to its familiarity with students (Kalogiannakis et al., 2021). Additionally, it can facilitate the development of scientific thinking (Tsai, 2018), and it is compatible with scientific theories, methods, and learning strategies related to the teaching of science concepts (Tsai, 2018). Providing motivation and enjoyment is not common to all people, so there is a need to understand the characteristics and techniques responsible, taking into account the different needs, values, and interests of each individual (Böckle et al., 2017). Adaptive gamification, i.e. the adaptation of different gaming mechanisms and features based on each learner's actions, preferences, and characteristics, is a rapidly developing method that enhances the traditional gamification approach (Klock et al., 2020). Inherently, it is a more personalized, learner-centred method of teaching, using a specific set of elements that respond to the characteristics of each learner.

However, although teachers recognize the value of technology, they often fail to use it as a learning tool (UNESCO, 2017). Therefore, in order for teachers to be able to effectively integrate ICT in education in the context of new pedagogical changes, they should be exposed to new models and trained to apply them (Zourmpakis et al., 2022).

Furthermore, a training program following the Technological Pedagogical Science Knowledge (TPASK) model as a design framework (Jimoyiannis, 2010) has been developed to train teachers to effectively teach science concepts using an adaptive gamification environment in authentic classroom settings. The present study aims to investigate the extent to which practicing teachers use adaptive gamification environments to teach science relating to the water cycle, following their participation in a training program designed according to the TPASK model.

Consequently, after the in-service teachers conducted the instructional implementation and analysed the observational checklists and motivational questionnaires of the students, we will respond to the following research question:

RQ: What is the degree of effective utilization and pedagogical integration of adaptive gamification environments in science teaching by practicing teachers?

The Adaptive Gamification Application: “The Water Cycle”

For the needs of this study, the adaptive gamification application “The Water Cycle” was created. This open-world role-play simulation was built with the Unity3D engine. The theoretical framework that the application was based was Self-Determination Theory (SDT) and Marczewski’s Hexad typology, allowing dynamic tailoring game elements and mechanics to each student’s needs and motivational priorities. More specifically, upon entry, students complete a 24-item questionnaire to identify their dominant player type (e.g., Philanthropist, Achiever, Socializer) but also their two more adjacent ones. Based on this profile, the system configures the game environment by activating specific game mechanics that align with the user's main type, while also incorporating elements from their two adjacent types traits to ensure a balanced experience (Zourmpakis et al., 2023).

The application further personalized the educational process by integrating two distinct pedagogical strategies: Problem-Based Learning (PBL) and Inquiry-Based Learning (IBL). The PBL approach focused more on narrative driven mystery where students act as detective assistants. On the other hand, IBL positions them as university research assistants focused on structured experimentation, limiting the story side. To maintain engagement, a continuous adaptation mechanism monitors student progress and feedback through in-game dialogues, in order to adjust difficulty and provide real-time scaffolding if necessary, ensuring the learning curve remains appropriate for each user.

Methods & Context

The main interest of this study was to investigate how teachers will integrate and utilize the adaptive gamification application after completing a professional training program based on the TPASK methodology.

This study was conducted in a Mediterranean country in southwestern Europe. Data were collected using observation checklists by the researcher. The educational application included 5 teaching hours, one to prepare the students to use the application and one for each of the 4 scientific concepts taught, coagulation, melting, evaporation, and boiling. Overall, 6 in-service elementary 3rd grade teachers participated in this study. The implementation took place in their school's computer labs. Data were collected using observation checklists by the researcher. An observation checklist was completed for each teaching session. The researcher was present during

these sessions to observe, fill the observation checklist and provide technical support only when strictly necessary (e.g., if students found "bugs" or ways to break the game boundaries), ensuring the teachers remained the primary facilitators. The observation checklists were analysed qualitatively. Additionally, this research followed all formal national and international rules for ethics in research, including obtaining written consent from parents and from students.

Albeit the small sample of teachers, we followed a semi-experimental design with a convenience sample, following a robust ethical protocol through the following:

(a) observational checklists were checked by external researchers to verify clarity and connection to the TPASK model

(b) to ensure the validity of this study, all data could be accessed and reviewed by external researchers

(c) data were analysed through the use of ATLAS.ti software.

This approach allowed for first-hand data collection where teachers' interaction with students occurred naturally, as opposed to relying on secondary reports that could be obtained through interviews. The process involved completing an observation method which involved having a comprehensive checklist with detailed explanations in each TPASK domain, providing a thorough description of each teaching case. In addition, increasing student motivation is the direct purpose of gamification. Thus, it was deemed necessary also to measure student motivation in order to be able to ascertain whether the practical application is influenced by student motivation.

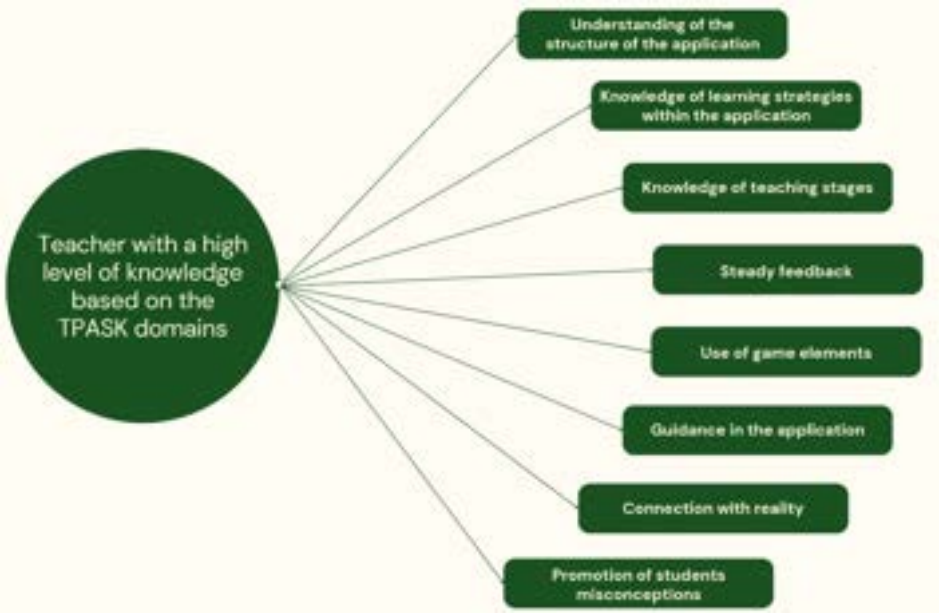
Findings

Based on our findings two main categories of teachers were identified. The primary criterion for this categorization was the actual utilization of the application during teaching, as the effective pedagogical integration of technology is the ultimate goal of the TPASK framework.

The first type, which consisted of half the sample size, appeared to have considerable knowledge of the application. applied appropriate teaching strategies, and incorporated game elements to enhance student motivation. To be more specific, these teachers demonstrated a comprehensive understanding of the structure of the application and were well-prepared, possessing specific knowledge of the learning strategies embedded within the software and how to identify them. They applied appropriate teaching strategies and knew the specific teaching stages required to help students at every step. Moreover, they were distinguished by their ability to relate the application to reality and to support students' conceptual understanding by highlighting alternative conceptions and guiding them toward conceptual change. An important factor of their teaching was their provision of steady feedback during experiments and review discussions. Furthermore, they consistently incorporated game elements and mechanics to enhance student motivation and engagement.

However, their performance was not high from the start, as almost all had some initial difficulties in the first lesson implementation, but showed gradual improvement, especially in areas such as guidance within the application and the integration of gamified elements. Also, even though they showed high levels of TPASK knowledge, they faced some difficulties with technical issues that came up during the lesson implementation in all lessons.

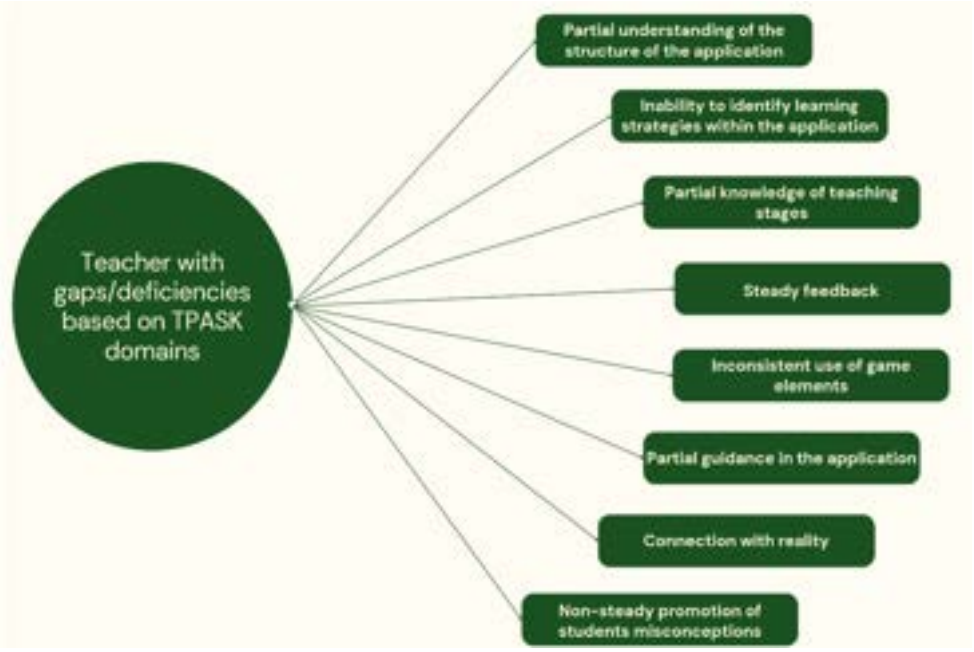
Figure 1. The specific characteristics of type 1: Teacher with a high level of knowledge based on the TPASK domains.



The second type included the rest of the sample size and showed deficiencies in the preparation and use of the app, as well as in the management of learning strategies. This group was characterized by a partial understanding of the application's structure and a lack of full integration of the scientific inquiry process through the digital tool.

In particular, although they made an effort to support students, they exhibited an inability to identify specific learning strategies within the application and had only partial knowledge of the necessary teaching stages. They struggled with linking technological knowledge with pedagogical and scientific knowledge, resulting in a failure to consistently integrate experiments and game elements into the educational process. Despite these gaps, they did attempt to provide steady feedback to students during the explanation of phenomena. However, their promotion of student misconceptions and reflection was non-steady and inconsistent. They also had similar problems in solving technical issues and reported more significant concerns regarding time constraints and classroom management.

Figure 2. The specific characteristics of type 2: Teacher with gap/deficiencies based on TPASK domains.



Importance

The findings of this study, though they can't be generalized due to the small sample, show the importance of training teachers in the use of adaptive gamification environments through specialized professional development programs based on the TPACK framework, particularly adapted for teaching science education (TPASK) and applying it practice. Additionally, based on students' engagement during the implementation, of it can be suggested that applying adaptive gamification environments in teaching can have a positive impact on students' motivation, even in cases where the teacher shows deficiencies regarding implementation. This could become clearer later with the analysis of the students' motivational questionnaire and teachers interviews in a later stage. Integrating technologies into education through TPASK requires balanced knowledge and skills development, with a focus on practical application and reducing the complexity of tools (Rochintaniawati et al., 2018).

Taking into account the role of the teacher in the learning process and their impact on students' learning experiences, especially when integrating technological tools into teaching (Kalogiannakis et al., 2021), it is important to design and provide appropriate training programs for current and future teachers. Based on the differentiations found from the utilization of classroom instruction (teacher types), we propose the creation of education/training programs where teachers' training is tailored based on their specific characteristics and needs. Additionally, the advantages of adaptive environments are not limited to primary and secondary education.

In addition, we propose the use of methodologies that are specialized both in the content of teaching and in the integration of technologies in teaching. By its nature, TPACK requires pedagogical methods and technologies tailored to specific topics (Voogt et al., 2013). Each subject has specific characteristics (e.g. learning strategies), which are sometimes specific to that subject (Jimoyiannis, 2010). Also, each technological tool has different capabilities and weaknesses. Treating technological tools in a generic way may result in not offering appropriate guidelines to improve teachers' professional development based on their abilities and weaknesses (Hsu et al., 2015). Creating a personalized learning system driven by the TPACK methodology would facilitate teachers' professional development (Chaipidech et al., 2022), while combining it with gamification could enhance their motivation and engagement.

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Developing Sustainable Professionalization Programs For STEM Teachers By Systematically Reflecting On Transfer Pathways

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Digitalization offers great potential for teaching and learning. To unfold this potential and support pre- and in-service teachers as well as students in schools to develop the competences needed for teaching and learning in a culture shaped by the digital transformation, a statewide program was initiated in the German federal state of Schleswig-Holstein. The program aims at developing and implementing innovative support structures on a personal, material and systemic level, thus addressing multiple target groups with the ultimate goal to implement the program at scale throughout the state. With its long-term orientation, its integration of all phases of teacher education and its approach to institutionalize the collaboration between the different institutions involved in teacher education, the program offers unique opportunities to systematically investigate transfer processes. Research in this field shows that enabling successful transfer is challenging - and often fails - because of the complex nature of factors influencing it. This paper will present findings from a systematic analysis of transfer pathways within the program based on a process model that accounts for the complexity of the program, conditions and interactions, using STEM subjects as an example. It will show the models' potential for the monitoring and synoptic reflection of transfer processes in large-scale intervention programs that can not only feed back into the program but may contribute to a better understanding of transfer in education in general.

Keywords: transfer processes, digitalization, teacher professionalization

Introduction And Background

Today's personal, social, and professional lives are shaped by digitalization (Stalder, 2016). Living in a culture of digital transformation is also affecting teaching and learning in many ways. Digital media have the potential to support teaching and learning processes and promote the acquisition of subject-specific and interdisciplinary competences and skills. At the same time, however, if you look e.g. at the opportunities arising from the use of artificial intelligence (AI) and big data, the subjects and disciplines themselves are changing as a result of increasing digitalization. From the perspective of important cross-cutting issues such as inclusion, heterogeneity and differentiation, or assessment, digital media enable new approaches of support for and design of learning processes. They pose, however, also challenges with generative AI being a prominent example: It opens up new possibilities for individual, formative support through intelligent tutoring and automated feedback systems, but at the same time poses challenges for traditional learning and examination formats. Moreover, thinking e.g. of fake news, it brings new aspects into traditional classroom instruction that need to be addressed. Ultimately, living in a culture of digital transformation requires digital and media-related skills, the acquisition of which is a cross-cutting task to which all subjects and disciplines must contribute (Redecker, 2017). Consequently, digital transformation also requires innovative formats for education and the way that we teach and learn. This does not only include the content or formats but also the conditions and actors that shape educational (systems).

However, across countries and educational systems, it can be observed that sustainably bringing educational innovations into practice is a widespread challenge leading to a limited impact of educational research on schools and teaching practice (e.g., Penuel et al., 2020). Research in this area faces the additional challenge that the process of "bringing into practice" incorporates not only different phases ranging from the development of an innovation, to its implementation, dissemination, and scaling-up, but also different concepts such as e.g. research-practice partnerships or teacher professionalization (e.g., Schrader et al., 2020). However, throughout different research fields these aspects and concepts are not consistently defined (e.g., implementation processes, innovations in school, school improvement, knowledge transfer) and sometimes used synonymously. In the last years, in the German-speaking literature, most of these aspects and research fields are summarized under the term transfer (e.g., Schrader et al., 2020). Therefore, in this contribution, we try to unify these existing aspects and constructs and define the interplay of development, implementation, and scaling-up as transfer processes.

Due to the great importance of transfer processes for the transformation of education, research in this area has increased over the last years. In a review study, Schrader and colleagues (2020) investigated factors supporting or hindering such transfer processes with a specific focus on the implementation phase. In total, they found 194 factors that are either related to the intervention itself (e.g., quality of material, fit to existing curricula) or the social environment of the learners (e.g., support, acceptance) as well as to institutional and organizational (e.g., autonomy, support, cooperation) or personal conditions (e.g., beliefs, self-efficacy). In their research, the authors used a utilization of learning opportunities model that allows not only for looking at different levels of context factors but also for taking the role of the target group as the ultimate user of transfer endeavors into account – a perspective often neglected in existing transfer models. One reason for this might be that for a long time a unidirectional understanding of transfer – with research being the provider and practice being the recipient – prevailed (e.g., Penuel et al., 2021; Tseng, 2012). More recent approaches, however, advocate for understanding transfer as bi-directional or co-constructive processes in which actors from research and practice bring in their respective expertise and collaboratively work together to enable educational transformation (Farley-Ripple et al., 2018; Penuel et al., 2021). Investigations in this field, however, are still scarce which might be due to a lack of models allowing to investigate this kind of transfer processes.

The growing importance of transfer within educational research is also reflected in educational policy and practice. Over the last years, a number of projects that explicitly aim at supporting transfer processes (in Germany e.g. the project lernen:digital[2]) have been funded. However, these projects often face the challenge that they are of limited duration. The successful transfer of innovations, though, requires longer time spans due its complexity but also a certain inertia of educational systems (e.g. Otto, Bieber, & Heinrich, 2019).

In this contribution, we present an investigation of bi-directional and co-constructive transfer processes in a long-term, statewide program aiming at the sustainable professionalization of teachers for teaching and learning in a culture shaped by the digital transformation. The findings from this investigation can make an important contribution to the development of sustainable programs for the transformation of education.

A Statewide Program For Fostering Digital Competences As A Context For Investigating Transfer Processes

As a response to the increasing demand by schools, teachers and teacher educators for support in addressing the challenges of the digital transformation but also harnessing its potential for

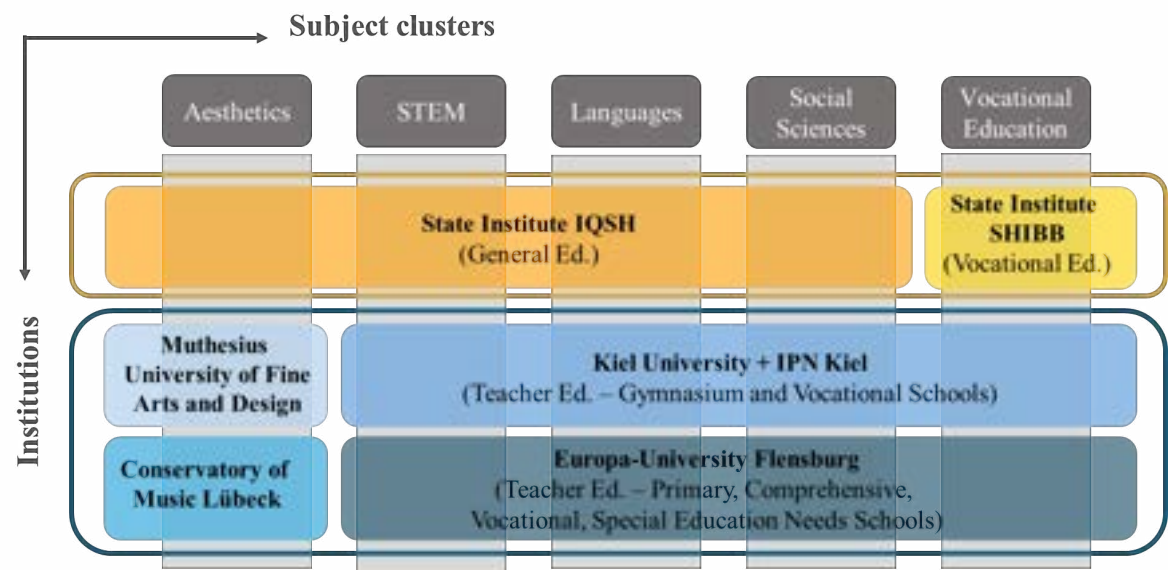
[2] https://lernen.digital/

enhancing student learning, a statewide program was established in the German federal state of Schleswig-Holstein. The program *Zukunft Schule im digitalen Zeitalter* (*Future School in the digital age*) aims at sustainably promoting the competence development of students and pre- and in-service teachers through a future-oriented approach to the potentials and challenges of an increasingly digitalized living and working environment. For addressing these aims, it

- … is conceptualized as a long-term, permanent support and intervention project,
- … addresses all subjects and all phases of teacher education (university/phase 1, teacher training/phase 2 ("Vorbereitungsdienst (VD)"), TPD/phase 3) and, ultimately, the competences of students, and
- … brings together all institutions involved in teacher education, namely the four universities offering teacher education programs in Schleswig-Holstein, the IPN Leibniz-Institute for Science and Mathematics Education, the two state institutes (for general and vocational education) responsible for VD and TPD and the Schleswig-Holstein Ministry of Education.

The program focuses on fostering general digital competences (such as media and technological competences) as well as subject-specific (e.g., the potential of microcontrollers in science education) and transdisciplinary competences (e.g., education for sustainable development). This is reflected in its organizational structure that builds upon two pillars. The media competence pillar consists of four regional media labs and media consultants who offer school counseling and TPD activities regionally in the different state districts. Within the subject cluster pillar, teacher educators at the state institutes (called *Regional Subject Consultants, RSC*) and the universities (called *Educational Engineers, EE*) collaboratively develop and implement support activities for pre- and in-service teachers in five subject clusters, thus bringing together expertise and perspectives from research and practice (see Figure 1).

Figure 1. Research-practice collaboration within the organizational structure of the state program.



Their activities include e.g. university, TPD and self-study courses; school development days; lecture series; exhibitions; digital work shadowing; OER teaching and learning materials or courses for teacher trainers but also supporting curriculum development at schools and universities.

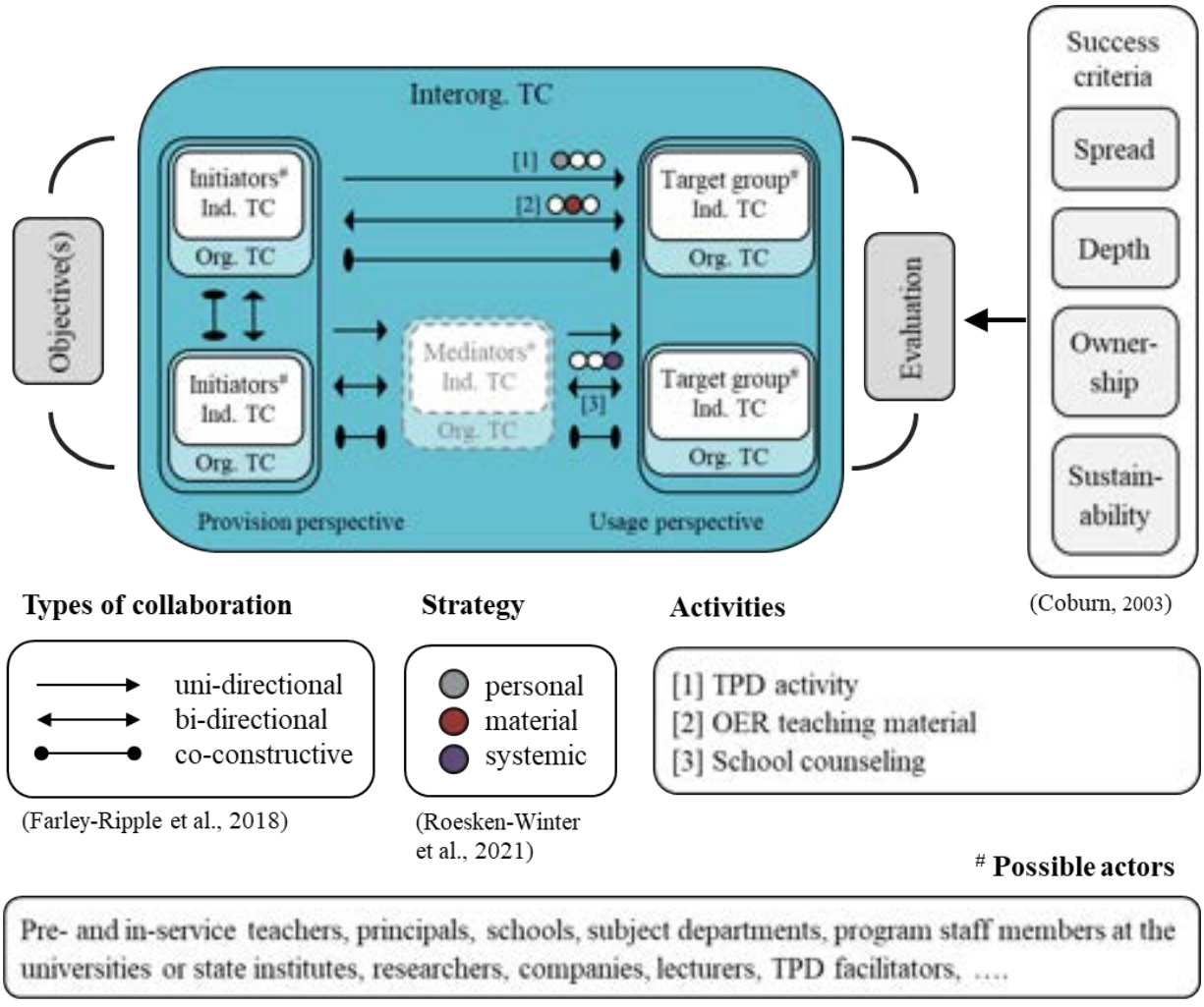
The concept and structure of the state program thus not only address the challenges and opportunities of the digital transformation but explicitly acknowledges what is known about

successful transfer. It thus provides promising conditions for investigating transfer processes with a specific focus on bi-directional and co-constructive collaboration.

A Model To Monitor And Reflect On Transfer In Projects

The model presented in this section (see Figure 2) understands transfer initiatives as projects with a clear focus on transfer (flerlage et al., in press). While building on existing models of transfer, this model differs in its explicit focus on the processes and actors involved, allowing for the identification and pursuit of specific transfer pathways tailored to project goals. With this focus, the model is particularly suited for monitoring and reflecting on transfer in complex large-scale projects, in which many contributors with potentially different goals are involved.

Figure 2: Model For The Systematic Reflection On Transfer (Adapted From Flerlage Et Al., In Press).



Note: TC = Transfer Conditions, Interorg. = Interorganizational, Org. = Organizational, Ind. = Individual

The model represents transfer scenarios within a project as structured around three core elements: the definition of objectives (left grey box in Figure 2), the transfer process (big blue box in figure 2), and the evaluation of outcomes (right grey box in Figure 2). It can be used to investigate various pathways leading from the objective to the outcome. Larger projects as the presented state program may consist of multiple interrelated transfer scenarios including various pathways from the defined objective to the outcome. The evaluation of outcomes related to the objectives is conducted using suitable indicators, which may conclude the transfer scenario or function as an intermediate checkpoint to inform adjustments to objectives, actor involvement, and/or strategy.

A key feature of the model is its focus on the actors involved. From a provision perspective, transfer processes are set up by initiators, while from a usage perspective, they address specific target groups. Mediators may also be involved to facilitate the process. Actors can be individuals, groups, or institutions within educational contexts, such as teachers, principals, students, TPD facilitators, subject departments, researchers, companies, or schools. Importantly, actors can assume different roles depending on the transfer process, for example as initiators, mediators, or target groups. While initiators and target groups are essential components of any transfer process, the inclusion of mediators depends on the specific objectives and design of the transfer process. The actions of all actors are shaped by individual, organizational, and interorganizational conditions. Individual conditions include beliefs, motivation, self-efficacy, and competencies. Organizational conditions encompass factors such as institutional size, available resources, and incentive structures. Inter-organizational conditions involve aspects such as frequency of contact, trust, mutual recognition of expertise, and geographic or cultural proximity, all of which can influence collaboration and transfer effectiveness (Schrader et al. 2020, 27 f.).

The model also accounts for the variety of collaboration forms between actors. Depending on the objectives pursued, collaboration may be uni-directional, bi-directional, or co-constructive (Farley-Ripple, et al., 2018). Furthermore, different transfer strategies can be applied individually or in combination, including personal strategies (e.g., professional development activities), material strategies (e.g., provision of teaching materials), and systemic strategies (e.g., development of policy or strategy documents; Roesken-Winter et al., 2021). These strategies and forms of collaboration may vary across actors within a single transfer process, allowing objectives to be pursued through tailored combinations of approaches.

Finally, the model supports the systematic evaluation of transfer outcomes through goal-aligned indicators. For example, the four criteria proposed by Coburn (2003) can be used: reach (the involvement of multiple institutions and actors), depth (changes in beliefs and practices), ownership (identification with and responsibility for the transfer product), and sustainability (continuation beyond initial funding phases). These criteria provide a flexible foundation for operationalizing indicators that are adapted to the objectives of each transfer initiative.

Overall, the model's strength lies in its flexibility, capturing the dynamics of actors, collaboration forms, and transfer strategies across different phases of transfer processes. Rather than depicting prototypical processes, it provides a framework for the systematic analysis and of diverse transfer initiatives within a project. In this way, it supports both the scientific analysis and the informed design and optimization of transfer processes in educational research and practice.

Investigating Transfer Pathways

The complex conceptualization of the state program and its broad and all-encompassing overarching objectives provide opportunities but also challenges for transfer, among others, the multitude of formats, content, target groups, strategies and actors. To counteract this complexity and make beliefs about expected effects, decisions and related actions visible, the model presented in the previous paragraph is used to exemplarily map, describe and analyse different transfer scenarios – and the corresponding transfer pathways – pursued within the program. The underlying assumption is that looking into the specific transfer pathways from a program perspective will not only provide insights into objectives, beliefs and how these influence the decision for e.g. specific target groups, contents or formats, but also into the nature of interactions that hinder or support transfer at different stages of the process. On the individual level, visualizing one's own cooperations, formats, target group(s), etc. and explicitly describing objectives and outcomes of different transfer scenarios might support and lead to a more strategic and reflective process of planning one's own work. Thus, applying the model in the program

potentially serves two purposes: 1) giving an overview about different transfer pathways within specific transfer scenarios already "implemented" for further systematic and strategic decisions and, by fostering self-reflection, 2) acting as a systematic tool for planning and reflecting on transfer scenarios in a more holistic way.

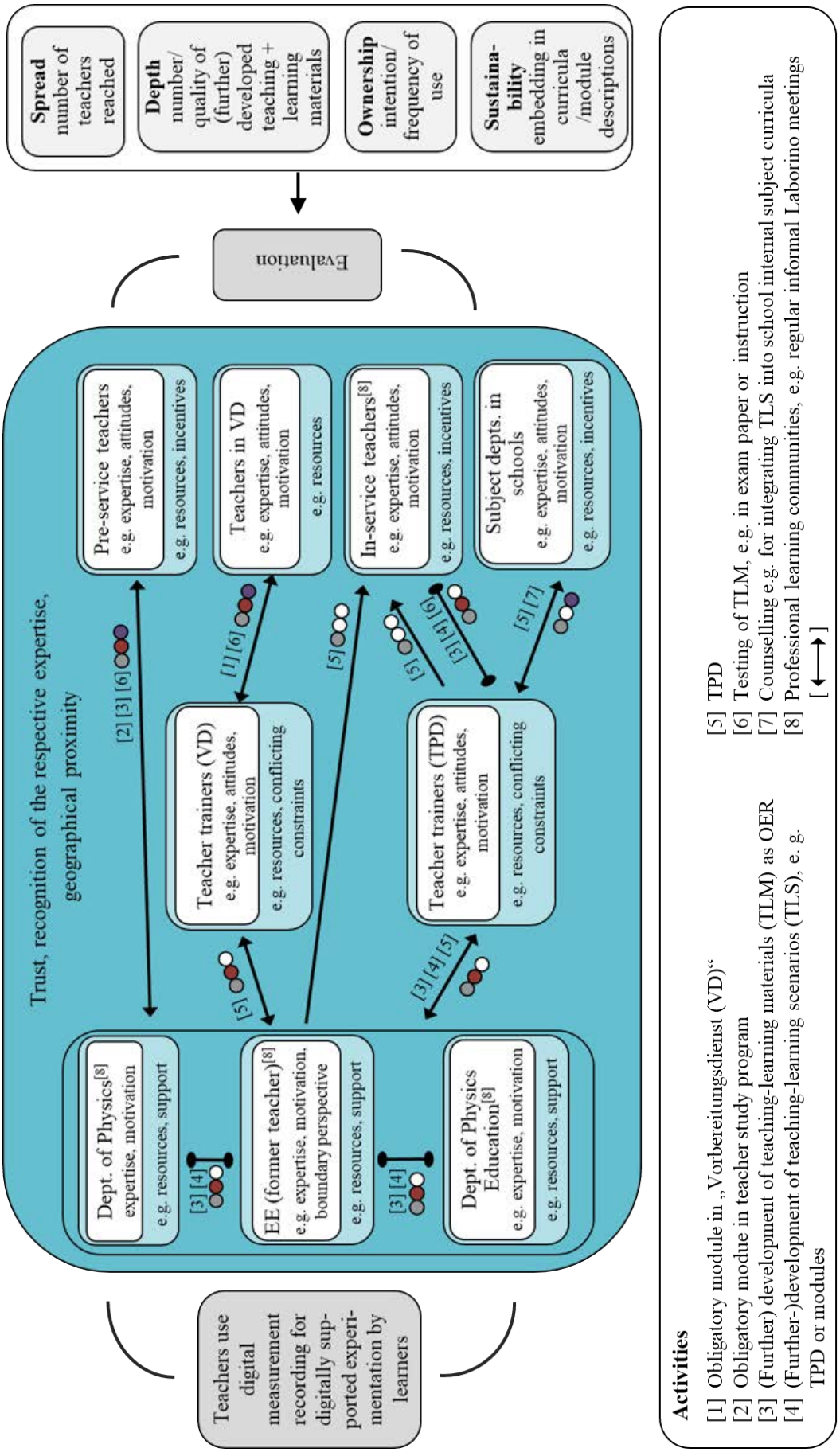
To address these purposes, the model was presented to the program staff working in the five subject clusters. Thereafter, they were asked to use it to describe and visualize examples of transfer pathways within one or two transfer scenarios from their clusters. The resulting graphical representations were then discussed with two of the authors and, if necessary, revised. In addition, the providers of the examples were asked about their experience of working with the model and their feedback was collected.

In the following, one example of a transfer scenario from the stem subject cluster including various pathways will be described in detail to illustrate the analysis approach and the work with the model. The example was chosen because it represents a rather complex scenario initiative, thus showing the potential of the model to visualize complex transfer pathways including several target groups such as pre- and in-service teachers.

Example Of A STEM Transfer Scenario

The chosen example is from the field of physics education (see Figure 3) and acknowledges the potential of digital measurement recording for science teaching and learning (e.g. Abdiakhmetova et al., 2024; Papadimitropoulos, & Pavlatou, 2023). The overall objective is to increase teachers' use of these systems in student experiments. To support teachers in developing the necessary competences, beliefs and attitudes to reach this objective, a transfer process integrating different actors from all phases of teacher education is used. This not only enables a coherent acquisition of competences but also acknowledges that beliefs tend to be robust and difficult to change (e.g. Tillema, 1998; Fives & Buehl, 2015). With the Educational Engineer acting as the central initiator, researchers and educators from physics and physics education co-constructively develop teaching and learning materials and scenarios. In order to provide teachers with the necessary digital measurement technology, a digital sensor box was developed and is made available as an open educational resource. Its further development is an important part of the co-constructive transfer process. The teaching and learning materials form the foundation for subsequent support measures for pre- and in-service teachers (e.g. modules in the teacher study program or TPD courses) but also for teacher trainers working at the state institute or at schools in teacher training and TPD. In the context of the model, these teacher trainers act as mediators between the initiators and specific target groups. Introducing mediators in the transfer process allows to increase the spread by using them as multipliers but also contributes to the other indicators of successful transfer, e.g. by embedding the topic as an obligatory module into VD (increasing sustainability) or by counselling subject departments in schools (increasing ownership). In addition to these formal learning opportunities, the transfer process also incorporates professional learning communities as informal settings to encourage and support collaboration and exchange among teachers and between research and practice. As far as transfer conditions are concerned, from an individual perspective expertise and motivation play an important role. However, the expertise of the respective actors differs. On the initiators' side, researchers in the physics department contribute primarily technical and physics-specific expertise to the development and use of digital measuring devices as open educational resources, while researchers in the department of physics education contribute expertise in systematic integration into teaching and lesson plans. On the user side, in-service teachers contribute their expertise and experience to the co-constructive process, sharing what has worked well in their teaching and what is still needed.

Figure 3. Exemplary transfer scenario from physics education (for legend see Figure 2).



From an organizational perspective available resources, possible incentives and support are important transfer conditions. At the interorganizational level, the success of the transfer process depends on trust and appreciation of the respective expertise and perspective; it is supported by

a spatial proximity, e.g. all initiators and institutions involved are located in the same city and the teacher trainers are working regionally with schools and teachers in VD.

Conclusion: Challenges And Opportunities Of Working With The Model In The Program

Reaching the objectives of the state program requires successful transfer. The overarching aim of looking at transfer through the lens of the presented model thus is to support transfer at the program level by systematically analysing the different transfer scenarios that are pursued. Applying the model to examples from the STEM cluster but also across subject clusters showed the model's potential to systematically describe, analyse, and reflect on transfer pathways of varying complexity ranging from processes involving multiple initiators, target groups, collaborations and formats to simple ones like e.g. the development and implementation of a single module within a teacher education program. The graphical representations thereby visualize important factors influencing transfer like e.g. individual and organizational conditions, types of collaboration and transfer strategies as well as criteria to evaluate whether the outcomes are in line with the objectives. For example, it can be observed that truly co-constructive collaboration (Farley-Ripple, et al., 2018) is rare but is supported if contributors have the same subject background. Moreover, initiators usually pursue more than one transfer strategy to reach their objectives; they often combine material and personal strategies but yet seldom address the systematic level (Roesken-Winter et al., 2021). Overall, it became obvious that a lack of learning scenarios addressing the systematic level exists (e.g., teach-the-trainer workshops, multipliers, professional learning communities) which might give hints for strategic management and planning in the future.

In terms of evaluation and effects of transfer scenarios it can be observed that working with and discussing the model enables the visualization of the criteria and measurements of effects that are actually applied (Coburn, 2003). However, it also became obvious that an important target group stated in the program's objectives, namely school students, is only very seldom directly addressed by support measures. These focus almost entirely on pre- and in-service teachers as well as teacher educators in all phases of teacher education assuming that supporting and professionalizing these groups will have a positive effect on student learning.

Working with the (science) educators in the state program on describing and reflecting on transfer pathways related to the support measures they are developing and implementing revealed challenges but also opportunities at different levels. From a transfer perspective, formulating objectives in a way that they can guide a transfer process proved to be vary daring. Objectives tended to be very broad (e.g., fostering digital competences or supporting collaboration) or format- rather than content-related (e.g., developing a TPD activity or support). In addition, only limited attention was paid to evaluation criteria leading to the use of standard questionnaires that were often not aligned with the stated objectives and transfer getting confused with related concepts like effective TPD or the development of teachers' professional competence. Looking at challenges related to the specific use of the model, a tendency could be observed to report only on complex processes and consider any type of collaboration as co-constructive. The analysis, however, also revealed that the initiators of support activities often focus on the development and implementation of a specific format rather than regarding it as a transfer scenario and seldom included ideas for scaling up. Working with the model and trying to apply it to their own work, however, made them aware of this, thus making the model a valuable resource for self-reflection at an individual level, too.

Outlook

Overall, it can be summarized that applying the transfer process model to the program has been helpful in two ways. From a program point of view, analysing transfer through the lens of the model enables the investigation and visualization of transfer pathways that lead from an objective, over transfer processes of various complexity to outcomes. At an individual level, the contributors considered the model very valuable in guiding and structuring their work because it encourages and supports self-reflection. However, the model might not only be helpful in retrospective. It could also be used as a planning tool to guide transfer initiatives and design effective and detailed scenarios when initiating new projects or programs (Ward, 2019).

These first results are exemplary and have to be supported by further analyses in order to learn from comparing the different transfer scenarios and address questions like: How do objectives align with target group, content and formats? What beliefs exist regarding expected and expectable effects and how do these influence the decision for specific transfer pathways? What are individual and group-specific conditions for successful transfer of individual support measures? Moreover, additional analyses like e.g. social network analyses could provide information whether the collaboration structure envisioned in the conceptualization of the program – and in parts visualized in the transfer pathways – is reflected in the resulting networks. Answering these questions may not only feed back into the program to inform its further development but may also provide valuable insights for similar projects and programs and enhance the existing knowledge base on transfer.

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Professional Development In Out-Of-School Learning Environments To Promote Teachers' ICT Skills – How Can We Scale-Up Our Best Practice Examples?

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Research shows that teachers need to feel a degree of instructional autonomy, i.e., a sense of ownership, and self-efficacy to implement reform-based instructional practices learned in professional development (PD) courses. Certainly, PD has been shown to be crucial for teacher professionalisation and engagement. Criteria for effective PD, such as content-focused, collaboration, or activity-based approaches, have been elaborated. However, there is a great deal of variation between countries in how PD is organised, what topics are offered, who participates (voluntarily) and what the outcomes regarding teachers' (Information and Communication Technology, ICT) skills are. Accordingly, it is challenging to empirically identify what works best in PD courses, i.e., to identify examples of best practice that work in and for different teaching and school contexts. Our current Ministry-funded research and development project LFB-Labs-digital focuses on Science, Technology, Engineering, and Mathematics out-of-school laboratories as spaces for PD in teachers' ICT skills. Therefore, good practice within PD is being identified through questionnaires, interviews, and observations. We see great potential in a cross-country exchange of good, next and ideally best practices to improve PD provision. In this exploratory seminar, we discussed with international PD providers and researchers what examples of best practice look like, what data and criteria are used to identify them, how evidence-based approaches can be scaled up and implemented in different countries, and what recommendations can be derived for PD providers, researchers, and policymakers. To structure the exchange, we applied the placemat method, in which participants recorded and reflected their ideas and experiences.

Keywords: professional development, teacher education, digital learning

Introduction

Professional development (PD) is a central component of teachers' professional learning and an important lever for improving teaching and learning in schools (Drossel & Eickelmann, 2017; Priebe et al., 2019). In recent years, expectations on PD have further increased, particularly with regard to supporting teachers in responding to ongoing digitalisation and changing educational demands (Kultusministerkonferenz, 2020; European Commission, 2021; West & Leary, 2024). Although a growing body of research has outlined characteristics of effective PD (e.g. Desimone & Garet, 2015), its specific design and implementation continue to vary widely across educational systems, institutions, and national contexts. As a result, practices that are considered successful in one setting are often difficult to transfer to another.

This contribution is situated within this field of tension between established research knowledge and context-specific practice. It draws on an international exploratory seminar that brought together researchers, professional development providers, and practitioners from Germany and the United States. The exploratory seminar offered an opportunity for shared reflection on PD

focusing on teachers' ICT-related competences and on the conditions under which good or best practices can be meaningfully adapted and disseminated. By examining different perspectives and experiences, we seek to illuminate challenges and opportunities related to scaling PD across diverse educational contexts.

Theory And State Of Research

Beyond supporting individual growth, PD plays a central role in school and instructional development and ultimately affects the quality of student learning opportunities (Kultusministerkonferenz, 2020; European Commission, 2021; West & Leary, 2024). Against this backdrop, research has identified several core features that contribute to the effectiveness of PD initiatives. For example, Desimone and Garet (2015) highlight content focus, active learning, coherence, sustained duration, and collective participation as central criteria. Similarly, Lipowsky and Rzejak (2021) propose an adapted offer-and-use model, which outlines ten features of effective PD, including the quality of instructional design, the organisation of learning activities, and the professional expertise of the facilitators. These frameworks emphasise that PD must go beyond isolated workshops and be embedded in sustained, collaborative, and practice-oriented formats.

However, there is still considerable variation in how PD is structured and delivered across countries and even within regions of the same country (OECD, 2020). This includes differences in the topics addressed, the degree of voluntary participation, the resources allocated, and the resulting outcomes for teachers and students. Such diversity poses challenges for identifying universally applicable best practices for PD, as their success often depends on local educational traditions, systemic conditions, and teacher needs (Hayes et al., 2025). Recent studies also stress the importance of organisational factors, such as school culture and leadership support, alongside teachers' individual characteristics for successful PD implementation (Beavers, 2009; Hayes et al., 2025).

A key area of current concern is the integration of digital technologies into teaching and thus into PD. Despite investments in digital infrastructure, the actual use of information and communication technology (ICT) in classrooms remains limited (Eickelmann et al., 2024, Gil-Flores et al., 2017). This highlights the importance of PD that not only strengthens teachers' ICT skills but also supports the development of digital pedagogical competence, as described by frameworks such as TPACK (Mishra & Koehler, 2006) and DigCompEdu (Redecker, 2017). PD programmes in this field must enable teachers to critically reflect on their own beliefs about digitalisation, integrate technological tools meaningfully with subject content and pedagogy, and prepare students for participation in a digitally mediated world (Ertmer et al., 2012; Vogelsang et al., 2019).

Out-of-school learning environments, such as out-of-school labs, provide a promising yet under-explored context for teacher PD. Traditionally designed for students, these laboratories, often located at universities or research centres, offer authentic insights into scientific practice and experimentation (Kirchhoff et al., 2023). More recently, they have also been used as spaces for teacher learning, including the development of ICT-related skills (Martens et al., 2022; Martens & Schwarzer, 2023). Preliminary results of our joint project *LFB-Labs-digital* (see Kirchhoff, Schwedler et al., 2024) highlight the importance of collaboration and sufficient PD duration, while challenges remain regarding sustainable implementation and broad participation (Lüsse et al., 2025), which aligns with international findings (Popova et al., 2022).

Aim And Subject Matter Of The Exploratory Seminar

Despite the findings of several recent studies, the question of how to scale-up and generalise good practices remains a pressing concern. The diversity of educational contexts in different countries necessitates a careful consideration of how best practices can be adapted to meet the unique needs of different teacher populations. For example, PD programmes designed for urban schools with access to advanced technological infrastructure may not be directly applicable to rural schools with limited resources. Similarly, cultural differences in teaching philosophies and student-teacher dynamics must be accounted for when designing and implementing PD initiatives.

Given these complexities, a cross-country exchange of best practices was conducted within the exploratory seminar as a means of improving PD provision internationally. The aim was to provide an overview of PD practices for teachers' ICT skills across different countries, with a particular focus on identifying and scaling up best practice examples, while also establishing international collaborations to evaluate and disseminate these practices. The key question was: How can we scale-up our best practice examples in PD?

Figure 1. Overview of the placemat and the guiding questions within that was used in the exploratory seminar. The questions were enlarged for better readability.



In the exploratory seminar several interrelated themes were examined: the identification of best practice in PD from a cross-country perspective, the data and criteria used to identify best practice, strategies for scaling and adapting successful approaches across contexts, and recommendations for PD courses. Participants were asked to share specific examples of best practice, to reflect on the influence of policy guidelines, and to discuss how research evidence can be balanced with practitioners' experience. The exploratory seminar also considered factors contributing to successful scaling, including both achievements and challenges, and examined recommendations from multiple perspectives: for PD providers, on combining evidence-based approaches with practical classroom applicability; for researchers, on suitable designs and methods to capture long-term impact; for policymakers, on structural and financial conditions required to sustain PD; and across all roles, on fostering effective collaboration.

We used the placemat method enabling participants to individually record and reflect their ideas and contribute to a collective dialogue around these guiding themes (Figure 1). The placemat method is a cooperative learning strategy with a graphical layout, implemented in this context in groups of four. It first allows for the individual documentation of participants' ideas, solution approaches, and responses to a given question, and subsequently supports the negotiation and recording of shared group results, which are then discussed with the whole group.

To structure and enrich the exchange, the seminar followed four main steps.

1. Collecting Individual Thoughts: Each wrote their own experiences and perspectives
2. regarding the guiding questions into the placemat while rotating the placemat after each round (5 min).
3. **Breakout Group Discussions:** Participants discussed in smaller groups the general conditions, data collection, criteria, and evidence regarding best practice PD examples.
4. **Group Reports and Open Discussion:** The group results were summarised and compared in a plenary discussion, allowing for reflection on similarities and differences across contexts.
5. **Conclusion and Follow-Up Plans:** The seminar concluded with outlining next steps, including the definition of work packages, future seminars or workshops, and potential collaborative projects.

Results Of The Exploratory Seminar

The following section presents the results from the group discussions within two groups, which were documented using the placemat method. Participants (N =8) from Germany and the United States took part, providing a comparative perspective on the topics discussed. Due to the focus of the participants on PD in general, it was not possible in this case to compare experiences regarding teacher PD in out-of-school labs or with a focus on teachers' ICT skills in different countries.

Defining Best Practice In International PD

The discussions emphasized several recurring elements that contribute to defining best practice in PD from a cross-country perspective. Clarity and structure were identified as essential characteristics ("clear program", "clear guidelines", participants group 1). Programmes with clear guidelines enable teachers and school leaders to estimate the required workload and time commitment, thereby increasing feasibility at the school level. In contrast, the absence of sufficient hands-on opportunities was noted as a weakness in many PD formats. Opportunities for dialogue among teachers, students, and school leadership were considered necessary to ensure relevance and applicability in practice ("have conversations with teachers, students, and head of school", participant group 2). A second theme concerned the transferability of international examples ("International examples must be translated to a common language, what sometimes is difficult to achieve", "They [PD] depend on national/regional learning objectives", participants group 2). Participants highlighted the challenge of translating practices into a common conceptual and linguistic framework, particularly when aligning them with diverse national and regional learning objectives. The consideration of teachers' needs emerged as another defining feature of best practice ("Ask teacher what they need/expect for these PD courses → hands on + practical material", participant group 2). Effective PD should be designed in consultation with teachers, incorporating hands-on activities, practical materials (including possibilities for borrowing resources), and systematic evaluation through mixed methods. The integration of digital tools was also considered important. PD initiatives should prepare participants to work with a range of devices and hardware. At the same time, policy guidelines were often perceived as insufficiently

supportive, with limited autonomy reported as a barrier ("policy guidelines did not help; too much top dow[n], too less autonomy"; "I generally find policy to be limiting", participants group 2). In several cases, practitioners chose to move beyond restrictive policy frameworks in order to pursue what they considered most effective. Another point was the role of collaborative structures and action research in large-scale PD projects ("In a very large PD project we developed three different collaboration groups and did Action Research. Each group had a unique facilitator and PI. Each had a slightly different focus depending on their [teachers'] interest", participant group 1). Establishing multiple working groups with differentiated focuses, supported by targeted facilitation, was seen as a productive strategy for accommodating diverse professional interests while ensuring sustained engagement.

Data And Criteria For Identifying Best Practice

Concerning the data and criteria used to identify best practice in PD from a cross-country perspective, participants emphasized the importance of engaging in conversations about plans and results, collaborative planning between teachers and researchers, and producing practically oriented publications. School visits were highlighted as valuable opportunities to experience local practices firsthand and understand the contextual possibilities ("learn from practitioners + listen to them", participant group 1; "visit schools to experience their work and their possibilities", participant group 2). A crucial starting point, according to participants, is the practitioner's own experience, which helps to establish initial expectations while also introducing them to new models and approaches. Collaborative approaches, such as design-based research, were seen as effective ways to share ideas, experiences, and evidence ("development of a shared views", "compare actions and research", participant group 1). Mixed methods – including interviews and questionnaires – were recommended to compare evidence with practitioner experience. The development of a shared understanding and the comparison of action research with research-based interventions were also highlighted as important strategies ("I include classroom teachers in the design, implementation, and assessment process. This is done through Participatory Action Research, Collaborative Action Research, and a lot of formative Assessment/Evaluation", participant group 1)", participant group 1). In addition, participants stressed the need to include classroom teachers in the design, implementation, and evaluation of professional development. This is often achieved through participatory, collaborative action research and formative assessment, using research instruments not only to collect data but also as reflective tools for teacher learning.

Scaling And Adapting Best Practice Across Contexts

Regarding scaling and adapting best practice across different contexts, participants noted that dissemination rarely happens directly; instead, it is often carried out through multiple platforms, including digital networks, websites, and professional development institutes ("I suppose that dissemination through several platforms (web, network, institute of PD) could be positive", participant group 2). Therefore, the idea of a best practice handbook or "how-to" guide, combining digital and analog formats for both providers and researchers, was suggested and discussed within the exploratory seminar as a potential tool. German participants emphasized the challenge of coordinating communication with a larger number of participants and schools, particularly when crossing regional or federal boundaries with differing curricula for PD ("Expanded to more schools – lead to higher time commitment of coaches. Also, more organization", participant group 1). Effective communication was highlighted by all participants as essential to ensure that both practitioners and researchers feel acknowledged and heard. Commitment from PD providers and additional organizational support were also seen as necessary, alongside collaboration with specific teachers (find a way to have a good conversation

to make sure that both (providers and researchers) feel ‘good and heard’”, participant group 2). Teachers can act as multipliers, engaging their colleagues at their own schools. Long-term cooperation with laboratory schools was described as particularly effective, often yielding more substantial outcomes than initially expected, despite the understanding that teachers have a mind of their own.

Recommendations And Take-Away Of Own PD Courses

As last aspect, recommendations and key takeaways for designing effective PD courses were discussed. Regarding the role of PD providers, participants suggested using design-based research in collaboration with teachers, visiting schools to gain firsthand experience, and including assessments on specific topics as well as sufficient time for reflection. For researchers, longitudinal and cross-sectional studies as well as mixed-methods approaches were recommended to gain deeper insights, with a particular emphasis on qualitative research. From a policy perspective, participants highlighted the need for sufficient funding, clear communication, blended formats combining digital and in-person elements, and overall commitment to make PD feasible and sustainable. It was noted that in the United States, teachers are often paid for participating in PD programmes, which appears to serve as a strong incentive for engagement. Participants discussed that implementing a similar approach in Germany could likewise enhance participation, but can hardly be implemented in the current system as PD is seen in Germany as part of the duties of a teacher. Across all roles, effective collaboration was seen as essential, with participants emphasizing discussion and action on equal footing. Inviting policymakers to PD courses was also suggested to strengthen mutual understanding and engagement. Additional recommendations included involving various stakeholders, integrating action and community action research, providing coaching throughout the planning and implementation phases, conducting interview-based studies, designing programmes with sufficient duration, establishing long-term cooperation, and ensuring ongoing communication (e.g., “programmes with enough ‘time’ might impact sustainability”, “long lasting cooperations”, participants group 2).

Discussion And Conclusion

The results of the exploratory seminar indicate that the dissemination of PD is a non-linear process that depends on structural clarity, participatory design, and sustained communication. PD programs with transparent structures regarding workload, time commitment and outcomes are more likely to be taken up and disseminated at the school level, whereas formats lacking hands-on components limit practical transfer. Hereby, the results underline former results in the context of teacher PD (Drossel & Eickelmann, 2017; Lüsse et al., 2025; Lipowsky & Rzejak, 2021).

The dissemination of PD content across contexts requires careful adaptation rather than direct replication. The discussions between participants from the United States and Germany have shown that national best practices cannot be replicated in other countries but must be translated into shared conceptual and linguistic frameworks and aligned with local curricula, policy conditions, and teachers’ needs. By doing so, this might be a chance to improve policies regarding teacher PD in different countries.

Teachers play a key role as multipliers in the dissemination process. PD initiatives that actively involve teachers in design, implementation and evaluation (e.g. through participatory action research or design-based research) support sustainable dissemination within and across schools. Collaborative working structures and long-term partnerships with schools further strengthen ownership and professional learning communities.

Dissemination typically occurs through multiple channels, including digital networks, institutional platforms, professional development institutes and school visits. Hybrid

dissemination tools, such as digital and print-based best practice guides, can support both practitioners and researchers. Effective communication across platforms is essential to ensure engagement and recognition of all stakeholders.

Finally, sustainable dissemination depends on supportive organizational and policy frameworks, including adequate funding, institutional commitment, and blended PD formats. Incentives for participation – as described by the participants from the United States in contrast to the opportunities in Germany where PD are part of the job as teacher – and ongoing collaboration among teachers, PD providers, researchers, and policymakers are crucial for ensuring that PD content is not only disseminated but also sustained over time. This exploratory seminar facilitated a cross-country exchange about individual experiences in the context of teacher PD. As it was not possible in this case to compare experiences regarding teacher PD in out-of-school labs or with a focus on teachers' ICT skills in different countries, further exchange or research would be of interest.

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Understanding In-Service Stem Teacher Professional Development Needs: A Literature Review

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As the global demand and importance for up-to-date STEM professionals increases, STEM education should flexibly follow the trends. One mechanism, how STEM teachers can stay up to date with changes in the STEM field is in-service teacher professional development (PD). In the last decades, there have been numerous reports about various STEM teacher PD solutions in various contexts. Also, the number of publications regarded STEM teacher PD needs is growing, therefore the present study aims to provide an overview of the complexity of this topic. As a result, a systematic study was carried out to identify STEM PD teacher needs both in terms of PD contents and approaches to PD. The selected 17 peer-reviewed publications were published between 2010 and 2024 in Scopus, Web of Science, and EBSCOhost databases. A comprehensive review of these empirical articles produced a total of 16 subthemes under the main PD content and approach themes.

The results exhibited that the dominant STEM teacher PD needs in terms of contents are the use of ICT in STEM teaching and learning and the teacher's deeper understanding of STEM subject contents; in terms of PD approaches – practice-based PD and systemic support. Finally, several recommendations for STEM PD sustainability and future research references are presented.

Keywords: STEM, In-service teacher professional development

Introduction

In-service STEM teacher professional development (PD) is a cornerstone for fostering high-quality STEM education. As scientific knowledge and instructional methodologies advance, it is crucial that practising STEM teachers continuously enhance their content knowledge, pedagogical skills, and practical classroom strategies. Effective professional development experiences not only support teacher growth but also translate into enriched learning environments for students and enhanced student results – the goal of STEM education (Surahman & Wang, 2023). Several scholars agree that recognizing and addressing in-service STEM teacher PD needs is central to designing meaningful PD programs, as adults learn according to their needs. Still, often the STEM teacher PD is built top-down – the contents and approaches to teacher learning within PD are dictated by higher authorities (Cooper et al., 2020). The investigation of various teacher PD needs has been ongoing for some time in research articles as well as in international studies (i.e., OCED TALIS), still to this date there is an empirical gap about the in-service STEM teacher PD needs. At the same time, the perspective from which teacher PD needs are defined (and simultaneously the teacher PD needs definitions) vary.

Conducting a literature review in this area is vital for several reasons. First, it provides a comprehensive overview of existing research, enabling educators, policymakers, and PD providers to discern models and strategies for in-service STEM teacher PD. Second, it can help to identify persistent gaps and future research avenues.

Aim Of The Study

The study aims to investigate the intricacies of in-service STEM teacher PD needs (in terms of PD contents and approaches), which can guide further research and practice development. More particular, we aim to answer the following research questions:

RQ1: From what perspectives (teacher, school leader, policymaker etc.) are in-service STEM teachers' professional development needs addressed and how are they defined in recent studies?

RQ2: What are the in-service STEM teacher needs in terms of PD contents and approaches?

It is worth mentioning, that in the present review, the authors themselves do not define what STEM teacher PD needs are; we aim to obtain an overarching view about STEM teacher PD needs, the definitions and perspectives from which STEM teacher PD needs are defined.

Method

This study investigates the PD and training needs of in-service STEM teachers through a systematic literature review guided by the PRISMA checklist (Moher et al., 2009). The review followed key stages: (a) eligibility and exclusion criteria, (b) identification review, (c) screening, (d) eligibility, and (e) data abstraction and analysis. The process began with identifying relevant keywords and creating search strings for Scopus, Web of Science, EBSCOhost, and Google Scholar, as detailed in Table 1. Articles were then screened based on inclusion and exclusion criteria (Table 2), with automatic sorting functions used to streamline the process. The overall selection process is illustrated in the PRISMA flow diagram (Figure 1). Out of 85 initially screened papers, 43 articles were assessed for eligibility, and 21 were excluded for reasons such as including both pre-service and in-service teacher participants or lacking direct relevance to STEM PD needs. The final selection of studies was critically analysed to synthesize key findings, ensuring a rigorous and focused review aligned with PRISMA principles.

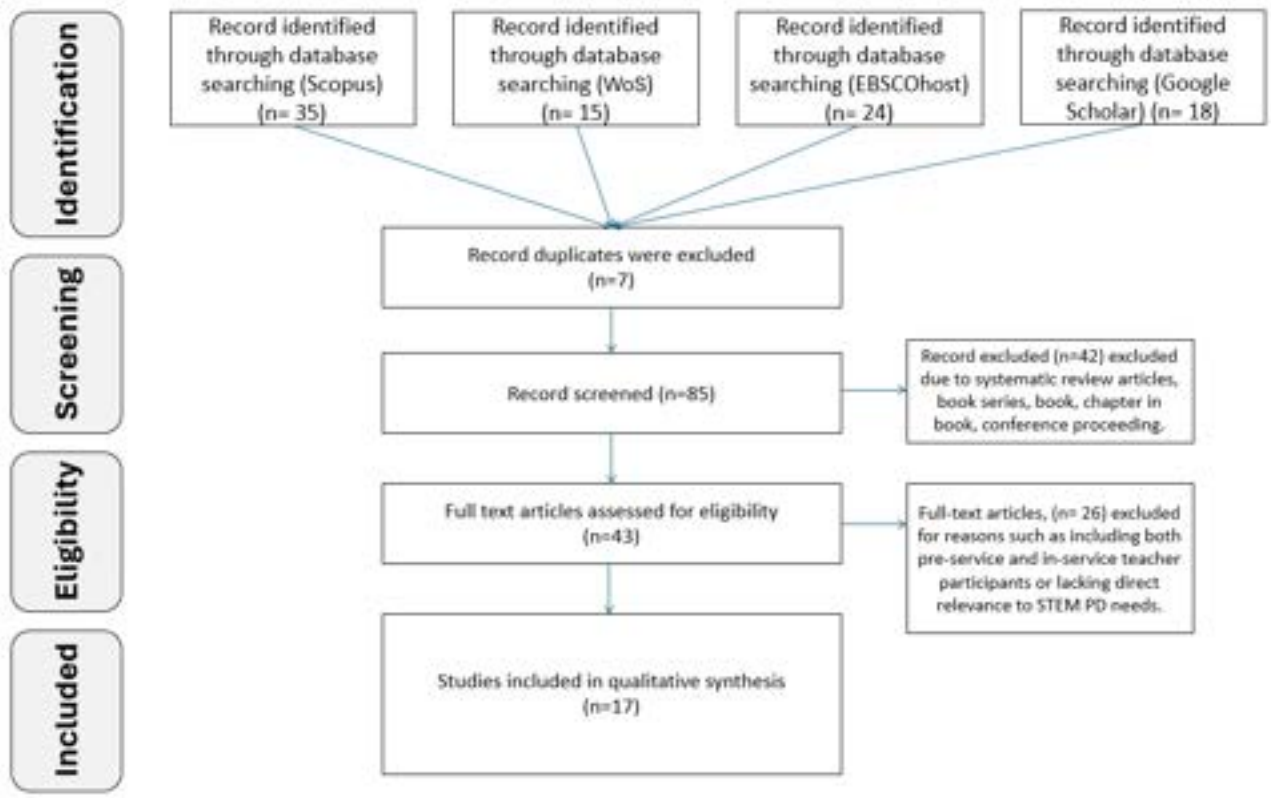
Table 1. Strings used during the search.

Databases	Search String
Scopus	TITLE-ABS-KEY(('STEM professional development' OR 'teacher professional development') AND ('In-service teacher' OR 'PD needs' OR 'Teacher needs' OR 'Teacher training needs'))
WoS	TS=(('STEM professional development' OR 'teacher professional development') AND ('In-service teacher' OR 'PD needs' OR 'Teacher needs' OR 'Teacher training needs'))
EBSCOhost	(('STEM professional development' OR 'teacher professional development') AND ('In-service teacher' OR 'PD needs' OR 'Teacher needs' OR 'Teacher training needs'))
Google Scholar	"STEM professional development" OR "teacher professional development" AND "In-service teacher" OR "PD needs" OR "Teacher needs" OR "Teacher training needs"

Table 2. The inclusion and exclusion criteria.

Inclusion Criteria	Exclusion Criteria
Studies focusing on in-service STEM teachers (science, technology, engineering, and mathematics).	Studies focusing on pre-service teachers or teacher candidates.
Articles that explicitly address professional development needs or teacher training needs.	Articles that do not explicitly mention STEM disciplines.
Peer-reviewed journal articles, conference papers, and reputable reports published in the last 15 years (2010-2025).	Opinion pieces, editorials, and non-peer-reviewed sources.
Research was conducted in diverse educational contexts, including primary, and secondary contexts.	Studies published in languages other than English (due to resource constraints).
Studies employing qualitative, quantitative, or mixed methods approaches.	

Figure 1. PRISMA flow diagram.



Findings

The reviewed studies span multiple continents, providing a comprehensive view of in-service STEM teacher PD needs. The research was conducted across North America (USA), Europe (Lithuania, Northern Ireland, Greece, Portugal, and Germany), and Asia (Taiwan, Malaysia, Turkey, Israel, and the Philippines), showcasing diverse educational contexts and priorities. Sample sizes ranged widely, from small-scale studies with as few as 5 participants in Lithuania to extensive surveys involving up to 4,957 teachers in the USA, offering both localized insights and broader comparative analyses. The studies employed various research methodologies,

including quantitative, qualitative, and mixed methods approaches. Quantitative studies, such as those conducted in the USA, utilized structured questionnaires for systematic data collection. Mixed methods approaches, combining surveys and interviews, were used in studies from Taiwan, Malaysia, and the Philippines, enabling both statistical analysis and nuanced qualitative insights. Meanwhile, qualitative methods, including case studies, interviews, and teacher reflections, were prominent in studies from Israel, Turkey, and Greece, offering a deeper contextual understanding of PD needs. This methodological diversity enriches the overall findings and highlights the complexity of STEM teacher PD globally.

In terms of in-service STEM teacher PD needs definitions, only one of the reviewed studies (Zakaria & Daud, 2009) included a definition of needs (still not in the context of STEM teacher professional development needs): “need is defined in terms of want or preferences of an individual or a group of people. Need in this context is seen as a want (which implies interest or motivation), felt by an individual or group to eliminate a lack (Queeney, 1995).” Nevertheless, many of the reviewed studies include the perspective from which STEM teacher PD needs are viewed. For example, the study by Shernoff et al. (2017) includes the perspective in the study research questions: “What are the greatest challenges [for STEM teachers] to effectively implement integrated approaches to STEM education? What supports would be most helpful to overcome these challenges?”. Overall, all of the reviewed studies view STEM teacher PD needs from the teacher's perspective and define STEM teacher PD needs as challenges that STEM teachers face in their practice.

In the table below the identified 16 subthemes under the two main themes: 1) STEM teacher PD content and 2) approach needs are outlined.

Table 3. The themes and subthemes of in-Service STEM teacher PD needs identified in the present review (For the list of references of the reviewed articles, please use this LINK).

Publications	PD approach needs							PD content needs							
	Short PD	F2F	School-based	Practice-based	Systematic support	Ready-to-use materials	Collaborative	Reflective	ICT	Inquiry-based learning	A deeper understanding of the contents	Problem-solving in STEM lesson	Classroom management	Student collaboration	Assessment	Real-world issues
Zakaria & Daud (2009)									x		x	x	x			
Oztay et al. (2022)				x	x				x	x	x			x		
Shernoff et al. (2017)				x	x				x		x	x			x	
Lai (2021)				x	x											
Herro & Quigley (2017)				x	x											
Even-Zahav et al. (2022)							x	x								
McElearney et al. (2019)				x		x	x									

Chin et al. (2022)													x		x			x				x		
Burke et al. (2022)													x					x						
Chen et al. (2021)			x			x							x		x		x					x		
Sadler et al. (2018)	x	x						x					x				x							x
Akgunduz & Mesutoglu (2021)													x											x
Juskeviciene et al. (2024)								x		x														
Spyropulo & Kameas (2020)											x							x		x				
Hasim et al. (2022)			x		x			x					x	x		x								
Costa et al. (2022)						x		x								x								
Owens et al. (2018)	x	x	x					x		x		x	x				x							x
Buscher (2022)													x					x						
Kang et al. (2021)					x								x											
Zhang (2015)														x		x						x		

Discussion

All the research articles view teacher-perceived needs and are based on teacher opinions. There is a lack of studies, where PD needs are viewed from other perspectives (school leaders, external experts).

There are noticeable similarities between the results of this review and the large-scale OECD TALIS 2018 survey (OECD, 2019), which identified teacher PD needs on a large scale: use of ICT in lessons; assessment; and classroom management are some aspects which converge and are STEM teachers' top priorities in terms of PD content needs. Teaching students with special needs differs - none of the reviewed articles in the present research, still it is one of the top needs in OECD TALIS. A deeper understanding of STEM concepts could be highlighted as a unique PD need for STEM teachers. The rationale for such a need is clear - as few of the reviewed studies uncover – STEM teachers are usually specialists in one of the STEM subjects. When STEM is taught as an integrated subject it is objective to lack knowledge about other aspects.

Systemic support, ready-to-use materials and practice-based approaches are the top PD needs from the perspective of PD approaches; such needs appear not only in small-scale qualitative studies but also in large-scale quantitative studies.

There aren’t a lot of differences between the PD needs of STEM teachers in countries from various regions. For example, studies by Oztay in Turkey (Oztay et al., 2022) and Shernoff in the

USA (Shernoff et al., 2017) outline quite similar STEM teacher PD needs both in terms of approaches and contents. This could be possibly explained by the comparatively recent popularity of integrated STEM worldwide.

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Aesthetic Learning Processes In Science Education – Cultivating Empathy And Curiosity For Nature In Primary And Middle School Science

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This paper examines how Danish primary and middle school science teachers can develop and implement aesthetic learning processes to foster students' empathy and curiosity for nature. The study focuses on integrating authentic macro photography and observational drawing within a science-didactic framework that encompasses Education for Sustainable Development (ESD), the Danish concept of "naturdannelse", i.e. nature connectedness. By incorporating these visual tools, teachers can create engaging science lessons that deepen students' understanding of natural phenomena and promote sustainable development. Data collected from both in-service and pre-service teacher training programs demonstrates the effectiveness of these didactic approaches in engaging both teachers and students.

Keywords: professional development, student engagement, sustainability

Introduction

Research indicates that children develop deeper understanding and retention of natural phenomena when they engage with them through sensory experiences (Shouse et al., 2007; Zinkernagel 2017, 2022). However, studies also show a declining trend in curiosity and empathy for nature (Shouse et al., 2007), an observation supported by our experiences as teacher educators at the University College of Copenhagen. While direct contact with nature is crucial for fostering curiosity, this presents a challenge given the limited weekly hours allocated to science lessons in Danish public schools (Bentsen & Jensen, 2012).

This work contributes to Education for Sustainable Development (ESD, e.g. UNESCO 2017) by exploring how aesthetic engagement with nature might foster the emotional connection and curiosity that underpin environmental care and stewardship. To address the constraint of limited classroom time and foster students' curiosity and engagement with nature, we propose bringing nature into the classroom' through the use of macro photographs and aesthetic learning processes. This paper presents our work incorporating instructor-captured photographs and observational drawing activities in pre-service and in-service teacher education. This approach aligns with outdoor didactics theory by complementing classroom teaching with indoor nature experiences (Jordet, 2002). This method provides teachers with didactic tools that promote student co-ownership and engagement, potentially leading to increased motivation and stronger connections to nature (Jordet 2002; Bentsen & Jensen, 2012).

Photographs and observational drawings serve as powerful tools for creating aesthetic experiences of nature in science education. Visual representations help students grasp complex concepts while creating engaging learning experiences (Alenezi, 2015; Andersen, 2022). By using authentic macro photographs and guiding students through iterative observational drawing and discussion, teachers facilitate direct engagement with scientific phenomena through nature's aesthetics. This approach enables students to develop deeper connections with their subjects of observation while enhancing their understanding of nature's complexity and biodiversity – essential foundations for sustainable development (Zinkernagel, 2017, 2022).

Methodology

Our methodological approach is grounded in Iskov's (2020) concept of "det dobbeltdidaktiske blik", i.e.. the double didactic lens and the pedagogic principle of modelling. This framework emphasizes the importance of having teachers experience learning activities as learners themselves, while also reflecting on how to implement these activities in their own teaching practice. By engaging teachers in the same type of aesthetic learning processes which they later can be expected to facilitate with their students, we as teacher educators create opportunities for both experiential learning and pedagogic (didactic) reflection.

The study reported here was conducted at the University College of Copenhagen (Københavns Professionshøjskole, KP), which offers both pre-service teacher education and in-service professional development programs. Pre-service teachers at KP complete a four-year bachelor's degree in teaching, with those specializing in science education receiving comprehensive training in both scientific content and pedagogic/didactic approaches. The in-service program offers already practicing teachers the opportunity to become science supervisors through a professional development degree which combines two modules focusing on pedagogical knowledge and research with three science education courses and a final independently determined capstone project.

In one of the in-service modules, we introduced macro-photography in science teaching implementing the double didactic lens. Participants first experienced the learning process as students by examining authentic macro photographs of insects, flowers, and other natural subjects. These photographs were taken by one of the authors, who is a successful amateur photographer, highlighting subjects such as local flora and fauna. Using these photographs as models, in-service teachers were then asked to create detailed observational drawings of the organisms (Figure1). The process included peer feedback sessions and refining their drawings based on the feedback received. This was followed by presentations of their work to the whole class, with a subsequent reflection session, shifting to the teacher perspective. In the reflection session, participants engaged in whole-class discussions analysing the pedagogic potential of this approach. The lesson finished with time allotted for the in-service teachers to plan implementation of the approach in their own practice.

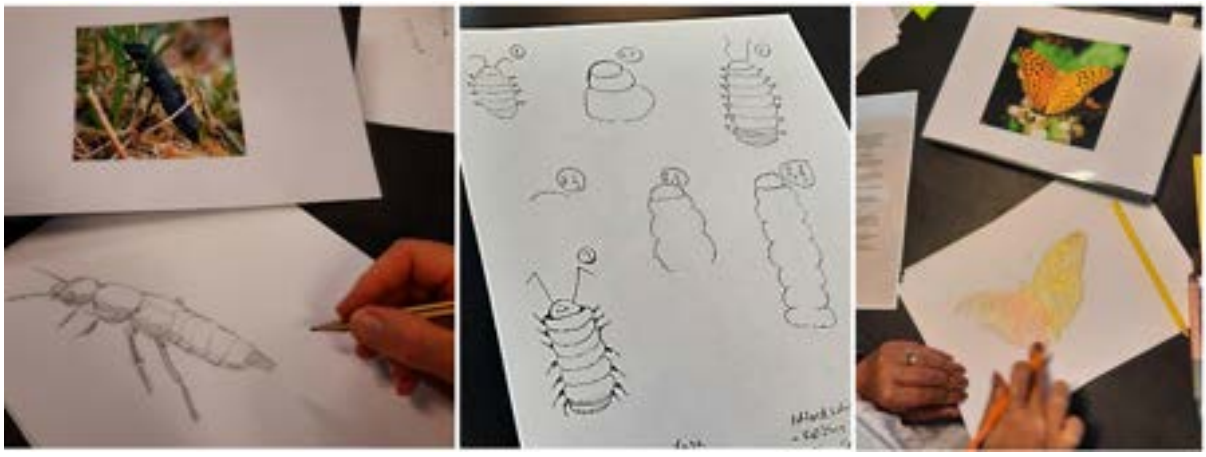
The lesson described for in-service teachers above was replicated with in-service teachers participating in a NAFA (Danish Academy of Science Education) project and with two cohorts of pre-service teachers in their first and third years of study, maintaining the dual focus (the double didactic lens) on personal experience and professional application.

Data

This paper draws on practitioner inquiry conducted within teacher education courses at the University College of Copenhagen. As course instructors, we implemented the macro photography and observational drawing approach described above with both pre-service teachers (1st and 3rd year cohorts) and in-service teachers within the context of the science supervisor program and NAFA´s professional development. Following their experience with these activities, some participating pre- and in-service teachers chose to implement similar approaches and were observed in their own classrooms (in grades ranging from Kindergarden to year -6, with students aged approximately 6-12).

Data presented here includes observations from our own teaching, teachers' created artifacts, and feedback collected through classroom discussions with pre- and in-service teachers. Figure 1 below shows examples of teachers' observational drawings.

Figure 1. Teachers´ observational drawings.



The subsequent classroom implementations provided additional observational data, including students' drawings and unstructured reflections with the participating teachers. Figure 2 below shows examples of observational drawings made by students and students, taking their own photos of insects found near their school.

Figure 2. Students' Observational Drawings And Taking Photos.



Finally, we conducted a survey-questionnaire with the teachers who implemented the approach with their students. The questionnaire includes four different themes according to our research interest in fostering students' empathy and curiosity for nature:

1. Empathy and Affection for Nature
2. Curiosity and Engagement
3. Understanding of and Communication about Natural Phenomena
4. Developing Nature Connectedness

Theory

The theoretical framework integrates multiple perspectives on learning and nature connection (e.g. Shouse et al., 2007). Beginning with aesthetic learning processes, research demonstrates how aesthetic experiences enhance motivation and engagement in science education (Zinkernagel, 2022). Visual learning theory supports the use of photography and drawing in

science education, showing how visual tools facilitate understanding of complex scientific concepts (Alenezi, 2015; Feldman & Lee, 2014).

Studies specifically examining macro photography and observational drawing highlight their effectiveness in fostering creativity and engagement (Antal et al., 2020). This visual approach aligns with the Danish concept of "udeskole" (outdoor education), which emphasizes the importance of bridging indoor and outdoor learning experiences (Jordet 2002; Bentsen & Jensen, 2012).

The Danish Outdoor Council further enriches this framework by identifying five essential dimensions for fostering children's nature connection (Hartmeyer & Præstholm, 2021):

1. Experiential Learning and Sensory Engagement: Macro photography and observational drawing enable detailed sensory interaction with nature in the classroom, allowing students to discover overlooked details and patterns.

2. Cognitive Development and Knowledge Acquisition: The process of careful observation and documentation through drawing promotes scientific investigation skills and deeper understanding of natural phenomena.

3. Emotional Connection and Appreciation: Visual engagement with nature through photographs and drawing cultivates emotional responses and empathy, fostering environmental stewardship.

4. Philosophical Reflection: The documentation process encourages reflection on humanity's role in ecosystems and environmental impact.

5. Material Engagement and Sustainability: Direct engagement with natural subjects through visual observation and documentation creates tangible connections to nature and environmental responsibility.

This theoretical framework supports our approach of using macro photography and observational drawing as tools for ‘bringing the outdoors in;’ when direct outdoor experiences are limited by time constraints, such aesthetic methods provide meaningful alternatives that maintain the essential connection to nature while also developing scientific observation skills.

Results And Findings

Our experiences implementing this approach in teacher education, combined with observations and feedback from teachers who subsequently tried it with their students, revealed patterns at two levels: first, the experiences of pre-service and in-service teachers as they engaged in the observational drawing process themselves; and second, their observations when implementing the approach with their own students in classrooms. Analysis of teachers' observational drawings, reflections, and feedback from course and classroom activities revealed insights about teachers' own learning experiences and patterns within four areas we had identified as central to our research interest: empathy and affection for nature, curiosity and engagement, understanding of and communication about natural phenomena, and developing nature connectedness. Below we present findings from both teacher learning experiences and classroom implementation, demonstrating how the double didactic approach functioned in practice

Teacher Experiences With Observational Drawing

When pre-service and in-service teachers engaged in the macro photography and observational drawing activities as learners, they consistently reported deep immersion in the observation process. As one teacher noted, "I became completely immersed in the task and forgot about time

while working."[3] This absorption appeared to stem from the detailed visual information provided by macro photographs, which revealed features that participants had previously overlooked. One teacher expressed surprise: "I was surprised by how little I actually knew about what the animal looks like."

The extended observation required by drawing facilitated what teachers characterized as slow and deep learning: "Working slowly gave me time to really notice details I would otherwise have missed," one participant reflected. This deliberate pace appeared to transform not only participants' understanding but also their emotional responses to their subjects: "An animal I initially found unpleasant became fascinating to explore."

Teachers acknowledged that the drawing process demanded perseverance, particularly at the outset. However, participants emphasized that success was more about technique than innate ability: "Drawing turned out not to be about talent, but about learning a technique." The scaffolding provided through video demonstrations and peer feedback proved essential, with one teacher noting, "The video and the feedback partner made it easier to get started."

The collaborative dimension emerged as particularly valuable, both for skill development and for generating science-related discussions. Through peer feedback and shared observation, teachers found themselves naturally engaging with scientific concepts and vocabulary. As one participant observed, "Talking about the animal helped me become more confident in using scientific terms." Teachers reflected that experiencing these challenges and discoveries firsthand enhanced their pedagogical understanding of how to implement the approach with their own students.

Student Implementation Findings

When teachers implemented these approaches in their classrooms with students ranging from kindergarten through 6th grade, four key themes emerged that illuminated how the aesthetic learning process functioned across different age groups.

Empathy And Affection For Nature

The most striking finding across multiple classroom implementations was a transformation in students' emotional responses to organisms they previously found unappealing or frightening. One 6th grade teacher observed: "The students saw the beauty of nature. Before, they screamed when they saw a spider in the classroom, but after these lessons, they went looking for spiders in nature and in the vicinity, just to look at them!" This shift from fear to fascination was echoed by another 6th grade teacher who reported being, "surprised that the students became so eager and affected to go out after the class session to find animals they previously found disgusting!"

Teachers attributed this change to the detailed visual access provided by macro photography. A 3rd grade teacher noted that, "especially the macro photos that allowed them to see all the many details up close gave the students enhanced joy and fascination of nature, something I don't usually see daily." The magnified perspective appeared to reveal aesthetic qualities in familiar organisms that students had previously overlooked or dismissed.

Curiosity And Engagement

The combination of viewing macro photographs and creating observational drawings generated sustained student engagement across all age groups. A 4th grade teacher reported that the approach, "created curiosity and motivation for further investigation into butterflies." This motivation extended beyond passive observation to active participation: "When the students were

[3] All teacher quotes have been translated from the original Danish to English by the authors of this article.

sent out, there was great engagement as they thought it was fun to take pictures themselves. The students were very curious when they were out taking pictures. It was very motivating to take pictures themselves."

The drawing process itself facilitated deep concentration, with one 6th grade teacher expressing surprise at observing students, "sit and immerse themselves in drawings of different species," a level of focused attention they had not previously witnessed in their science lessons.

Understanding Of And Communication About Natural Phenomena

Teachers observed that the detailed observation required for accurate drawing supported students' development of more precise descriptions and a need for related scientific vocabulary. A 6th grade teacher noted: "The students were able to name the animals and use technical terms such as horns, wings, hind legs, tail, etc. In addition, they learned to be concrete in their language." The iterative process of observing, drawing, and receiving peer feedback appeared to refine both students' visual discrimination and their ability to articulate what they observed using more appropriate scientific terminology.

Developing Nature Connectedness

Perhaps most significantly for long-term environmental engagement, participating students developed enhanced awareness of local biodiversity and their relationship to nearby nature. A 4th grade teacher reported that her students were, "especially surprised by how many different butterflies there actually were. 'They don't all look alike' – and 'do they really exist here!'." This discovery of diversity in familiar surroundings led to deeper connections: "The pictures opened up the butterfly-world more to the students, as they observed things that require the butterfly to sit still for a longer period of time. They became aware of the diversity, also in appearance. So, it created a desire to learn more about the butterfly."

A 3rd grade teacher emphasized the importance of using students' own nature experiences and photographs: "The students became more aware of what nature is and their local nature... Since it was their own nature-experiences and nature-images that we used, they also had to relate to their own experiences." Multiple teachers reported that students expressed "a desire to continue working with butterflies" and other natural subjects beyond the planned lessons. We see this as a solid foundation for further developing students' empathy and interest in nature.

Discussion And Conclusion

The implementation of macro photography and observational drawing in science education presents both opportunities and challenges that warrant careful consideration. Teacher reflections from both their own learning experiences and classroom implementations consistently highlighted several key requirements for successful practice. First, students require scaffolding and support in developing both observational awareness and drawing skills. As one teacher noted, success is, "not about talent, but about learning a technique." Second, what the teachers characterized as 'slow' and 'deep' learning facilitated by this approach demands dedicated time worth prioritizing even though it may conflict with curriculum pressures and the limited hours allocated to science instruction. Third, teachers need a clear pedagogical framework to guide implementation effectively, particularly in balancing aesthetic engagement with scientific learning objectives. These considerations are not limitations of the approach itself but rather indicate areas where teacher preparation and institutional support are essential for successful implementation.

Despite these implementation requirements, our findings demonstrate significant potential for this approach to address contemporary challenges in science education. While the four areas we

examined were informed by the five dimensions of nature connection identified by the Danish Outdoor Council (Hartmeyer & Præstholm, 2021), our findings validate this theoretical framework as a useful lens for understanding how aesthetic engagement supports nature connection.

The deep immersion and curiosity reported by both teachers and students reflects experiential learning through detailed sensory interaction. The transformation in students' emotional responses, from fear and disgust to fascination and care, embodies emotional connection and appreciation for nature. Students' awareness of local biodiversity and desire to continue exploring represents material engagement with their environment. Notably, several teachers reported students raising questions about ecosystems and biodiversity during the drawing process, touching on the dimension of philosophical reflection about humanity's relationship with nature. Students' use of more precise descriptive language and scientific vocabulary in articulating observations suggests cognitive development and knowledge acquisition. The iterative process of observing, drawing, and discussing appeared to create contexts where more precise language became useful for communication, an observation that warrants further investigation.

The convergence between our findings and established theoretical frameworks suggests that macro photography and observational drawing offer a viable pedagogical strategy for achieving the goals of "naturforbundethed" (in English: nature connectedness) even within the time constraints of contemporary schooling. Where Bentsen and Jensen (2012) and Jordet (2002) emphasize the importance of outdoor education for developing nature connection, our approach demonstrates how carefully selected visual materials can ’bring the outdoors in’, creating meaningful nature experiences when direct outdoor access is limited. The authentic macro photographs function as what we might call ‘windows to nature' providing the detailed, extended observation opportunities that are often difficult to achieve in traditional outdoor settings where organisms are small, mobile, or ephemeral. We believe that through providing such windows to nature in science lessons, students will become more curious and more motived to engage with nature outside the classroom. Teachers’ reflections on students’ wanting to take their own pictures of organisms reflect this.

The effectiveness of aesthetic engagement in generating scientific curiosity aligns with Zinkernagel's (2017, 2022) arguments for the role of aesthetics in science education. Teachers' observations that students discovered beauty in previously feared or ignored organisms suggest that aesthetic appreciation can serve as a gateway to scientific inquiry. This finding has particular relevance for Education for Sustainable Development (ESD), where fostering emotional connection to nature is recognized as foundational for developing environmental care and stewardship. The emotional and cognitive shifts we observed in both teachers and students represent important precursors to the deeper environmental engagement that ESD seeks to cultivate.

Our use of the double didactic approach (Iskov, 2020) in teacher education proved particularly valuable. Teachers who experienced the learning process themselves, engaging with photographs, creating observational drawings, giving and receiving peer feedback, developed both experiential understanding of the approach's power and practical insight into potential student challenges. This embodied knowledge appeared to translate directly into more effective classroom implementation, as evidenced by teachers' reports of increased confidence and their ability to anticipate difficulties and design appropriate scaffolding. The voluntary nature of classroom implementations further underscores teachers' genuine conviction in the value of this approach; those who chose to try it with their students did so based on their own transformative learning experiences.

Our findings across both pre-service and in-service teacher contexts suggest that the approach presented here is viable for teachers at different stages of professional development. These findings point toward broader implications for science teacher education. Traditional science methods courses often emphasize content knowledge and inquiry processes while giving limited attention to aesthetic dimensions of science learning. Our results suggest that explicitly addressing how visual tools and aesthetic experiences can support both affective and cognitive learning goals in science, have a valid place in teacher education programs. This is particularly important given the documented decline in children's connection to nature (Shouse et al., 2007) and the increasing recognition that environmental education must engage both head and heart. The double didactic approach offers a practical model for how teacher educators can prepare future teachers to use aesthetic engagement effectively, not as a supplement to science education, but rather as an integral component.

The success of this approach with students ranging from kindergarten through 6th grade, as reported by teachers across several implementations, suggests its adaptability across developmental stages. While the specific scaffolding varied by age group, with younger students requiring more support and older students capable of more sophisticated scientific engagement, the core process of careful observation, aesthetic appreciation and refining drawings proved engaging across the age range included.

The practitioner inquiry reported here demonstrates that macro photography and observational drawing offer a practical approach for cultivating both scientific understanding and emotional connection to nature within the constraints of contemporary classroom settings. By bringing nature indoors through aesthetic engagement, teachers can address the documented decline in children's nature connection while simultaneously developing essential scientific observation skills. This represents a contribution that aligns with both scientific literacy goals and the Education for Sustainable Development agenda.

While our findings demonstrate the potential of aesthetic learning processes for developing empathy and curiosity for nature, they also reveal opportunities for deeper investigation into how such approaches can support scientific literacy development. Our observations from both lessons with pre- and in-service teachers and with K-6 classrooms suggest significant potential for working more closely with subject-specific language and disciplinary dialogue. Teachers noted that students naturally sought more precise terminology as they attempted to describe and compare their observations. These finding warrants development and further investigation.

We hypothesize that through slow, attentive observation combined with structured collaborative discussion, learners can be scaffolded from everyday descriptions toward increasingly precise scientific understanding (Heinrich et al., 2024; Polias 2016). The need to accurately represent and communicate about organisms in their drawings appears to create authentic motivation for acquiring scientific vocabulary and engaging with disciplinary explanations. In this way, aesthetic engagement may serve as a dual function: deepening conceptual understanding while simultaneously motivating meaningful scientific communication.

While this practitioner inquiry establishes the viability of using macro photography and observational drawing to cultivate both emotional connection to nature and scientific observation skills, the approach warrants further development in two key areas. First, more systematic investigation is needed to understand how best to leverage aesthetic engagement for sustained nature connectedness and environmental stewardship. Second, future research should examine how this approach can be refined to more intentionally support scientific knowledge and science literacy development. Such investigations, conducted through more structured research designs across diverse educational contexts, will help establish the generalizability of our findings and

develop pedagogical frameworks that maximize the dual potential we have observed: fostering both affective engagement with nature and developing scientific literacy and understandings.

Acknowledgement

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Empowering STEM Teacher Professional Development Through AI Integration

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Artificial intelligence (AI) has revolutionized education by offering scalable, personalized, and interactive tools for teachers. This study investigates the potential of ChatGPT, an AI-powered platform, to enhance PD for primary school teachers, focusing on improving instruction in spatial ability—a critical skill for success in STEM disciplines. Grounded in constructivist learning theory, spatial cognition theory, and the TPACK framework, the research adopts a design-based research (DBR) approach to iteratively develop and evaluate a ChatGPT-supported PD program. The study utilizes a four-phase methodology: exploratory interviews, program design, classroom implementation, and program evaluation. Teachers integrate ChatGPT to design spatial ability tasks, generate lesson plans, and provide differentiated instruction aligned with STEM curricula. Data collection includes pre- and post-intervention assessments, reflective journals, focus groups, and lesson observations, analysed through the TPACK framework to assess the program's impact on teaching practices and student outcomes. This study highlights the potential of AI to transform teacher PD, offering insights into best practices for integrating AI tools into education while addressing challenges related to ethical use and overreliance. The findings aim to inform future PD initiatives and enhance STEM education at the primary level.

Keywords: Teacher professional development, spatial ability, ChatGPT, STEM

Introduction

Artificial intelligence (AI) is transforming education by offering innovative tools to enhance teaching and learning, particularly in professional development (PD) for educators. AI-powered platforms like ChatGPT provide unique opportunities to support teachers in designing, implementing, and refining strategies to foster critical skills such as spatial ability. Spatial ability—the capacity to visualize and manipulate objects in space—is a foundational skill for success in STEM disciplines, as it underpins problem-solving and conceptual understanding in subjects like mathematics, physics, and engineering (Uttal et al., 2013). Developing these skills in primary education is crucial, as early spatial reasoning correlates strongly with later academic achievement in STEM fields (Newcombe, 2010). Professional development plays a pivotal role in equipping teachers with the knowledge and tools needed to integrate spatial skills into their classroom practices effectively. Traditional PD models, while valuable, often face limitations in scalability, personalization, and real-time applicability. Here, AI emerges as a game-changer. Tools like ChatGPT can personalize PD experiences by tailoring content to individual teacher needs, providing immediate feedback, and generating diverse examples and instructional strategies (Holmes et al., 2022). Additionally, the accessibility of AI-driven PD solutions makes advanced methodologies more attainable for teachers, especially in under-resourced settings, ultimately enhancing both teaching practices and student outcomes. This study explores how AI can bridge gaps in traditional PD models, focusing on its potential to revolutionize the teaching of spatial ability in primary education. Still, every AI solution has its limitations and also can produce insufficient and/or biased answers.

Theoretical Framework

This study draws on two important frameworks for teaching & learning: the spatial cognition theory, and the TPACK framework. Spatial cognition theory (Uttal et al., 2013) underscores the malleability of spatial skills and their significance for STEM success. This study leverages these principles to enhance students' spatial skills through targeted teacher PD. The TPACK framework (Mishra & Koehler, 2006) integrates technology, pedagogy, and content knowledge, guiding the use of ChatGPT to align spatial skills strategies with STEM curricula. Grounded in design-based research (DBR) (Anderson & Shattuck, 2012), this study emphasizes iterative cycles to refine AI-supported PD, ensuring both theoretical rigour and practical relevance.

Aim Of The Study

The study aims to investigate the use of ChatGPT in enhancing PD for primary school teachers to improve spatial ability instruction. To achieve this, the study addresses the following objectives:

1. Investigate how ChatGPT can support teacher PD in improving spatial ability in STEM lessons.
2. Identify teachers' perceptions, challenges, and opportunities when integrating AI tools like ChatGPT into their PD.
3. Assess the effectiveness of ChatGPT-assisted PD compared to traditional PD methods.

Method

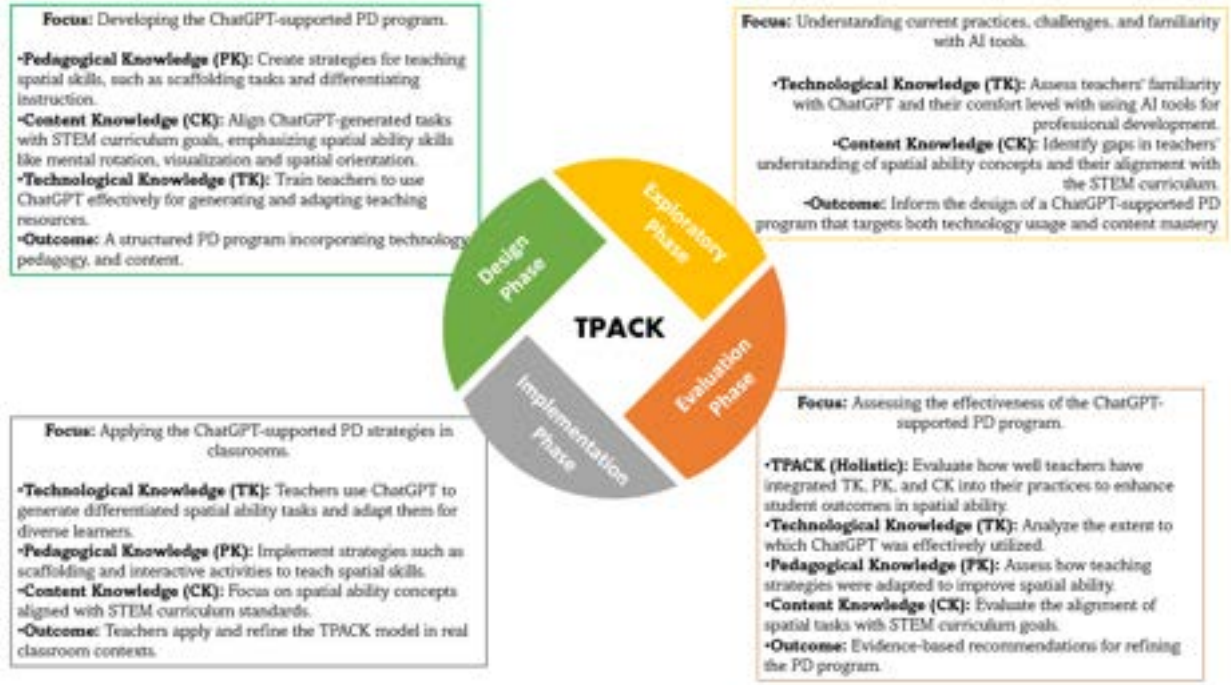
This study adopts a DBR approach, grounded in the TPACK and spatial cognition frameworks, to iteratively develop and evaluate a ChatGPT-supported PD program for primary school STEM teachers. The integration of ChatGPT serves as both a technological scaffold and a tool for aligning pedagogical strategies with spatial reasoning content. The DBR approach enables the refinement of the intervention through cycles of design, implementation, and reflection, ensuring both practical relevance and theoretical rigour (Anderson & Shattuck, 2012). The study involves 15 primary school teachers, selected through purposive sampling, who have diverse levels of experience in teaching STEM subjects. Their students (ages 8–10) are indirectly involved, with pre-and post-intervention assessments used to measure the impact of teacher PD on student spatial ability.

Phases Of Research

The study is structured into four key phases. In the exploratory phase, semi-structured interviews with teachers are conducted to understand their current practices, challenges, and familiarity with AI tools in their PD practices. These insights inform the design of a ChatGPT-supported PD program aligned with the TPACK framework, addressing gaps in technological knowledge (TK), identifying pedagogical strategies (PK) for teaching spatial ability and focusing on specific spatial skills such as mental rotation, spatial visualization and spatial orientation (CK). The intervention design phase involves developing a PD program consisting of workshops to train teachers on ChatGPT use, guided practice for aligning tasks with curriculum goals and adapting them for diverse student needs, and iterative reflections to refine their ChatGPT application. In the implementation phase, teachers integrate ChatGPT-supported strategies into their classrooms over six weeks. ChatGPT is utilized to generate differentiated spatial ability tasks, provide real-time feedback, and enhance lesson plans aligned with STEM curricula and developmental requirements. Finally, in the evaluation phase, both quantitative and qualitative data are collected through pre- and post-intervention tests, reflective journals, focus groups, and lesson

observations. These data are analysed using the TPACK framework to evaluate the integration of ChatGPT into teaching (TK, PK, CK), the alignment of spatial tasks with curriculum goals (TCK, PCK), and the overall effectiveness of ChatGPT in enhancing pedagogy and improving student outcomes (TPK, TPACK). In other words, to ensure that this phased approach ensures a comprehensive and iterative evaluation of the intervention, we set the TPACK elements as criteria for designing an effective STEM teacher PD solution that promotes teaching that supports student spatial ability. Figure 1 provides a visual representation of the DBR phases within the TPACK framework, illustrating how each phase is interconnected and aligned to enhance teacher development and student learning outcomes.

Figure 1. The DBR phases aligned with the TPACK framework, highlighting the integration of technological, pedagogical, and content knowledge in teacher PD for enhancing student's spatial ability.



The table below outlines how the TPACK framework was applied in the design and implementation of the ChatGPT-supported PD program. Each component of TPACK was strategically addressed throughout the various phases of the program's development and execution.

Findings

As this study is currently in its first cycle, findings are not yet available. The intervention is being implemented, and data collection will continue throughout the semester. By the time of the conference, the research will have completed all phases, including data analysis. Preliminary findings are expected to provide insights into how effectively ChatGPT supports teacher professional development for enhancing spatial reasoning skills and its impact on student outcomes. The conference presentation will focus on sharing these findings, discussing key themes from the qualitative data, and presenting implications for practice based on the quantitative results.

Table 1. Research phases aligned with TPACK components as design principles.

Phases	Component	Focus on PD Design	Annotation
Exploratory Phase	TK CK	Understanding current practices, challenges, and familiarity with AI tools.	**Activity:** Semi-structured interviews to assess teachers' current technological and content knowledge levels. **TPACK Focus:** Exploration highlights gaps in TK and CK, laying the groundwork for integrating these with PK in subsequent phases.
Design Phase	PK CK TK	Developing the ChatGPT-supported PD program.	**Activity:** Workshops for training on ChatGPT functionalities (TK), designing scaffolded spatial tasks (PK), and aligning them with curriculum goals (CK). **TPACK Focus:** The design integrates TK, PK, and CK to create a holistic program that fosters spatial reasoning.
Implementation Phase	TK PK CK	Applying the ChatGPT-supported PD strategies in classrooms.	**Activity:** Teachers integrate ChatGPT to design and implement lesson plans, aligning technology and pedagogy with STEM content. **TPACK Focus:** Real-time application of TPACK, enabling iterative refinement of teaching practices.
Evaluation Phase	TPACK (Holistic) TK PK CK	Assessing the effectiveness of the ChatGPT-supported PD program.	**Activity:** Analyse pre-and post-tests, focus groups, and reflective journals to assess TPACK integration. **TPACK Focus:** Evaluation synthesizes insights into how well TK, PK, and CK were integrated to improve teaching and learning outcomes.

Discussion

The TPACK framework, introduced by Mishra and Koehler in 2006, emphasizes the integration of technology, pedagogy, and content knowledge for effective teaching. Several studies have applied the TPACK framework to PD programs, demonstrating its effectiveness in enhancing

teachers' abilities to incorporate technology into their instruction. For instance, Bos (2011) highlights the integration of the TPACK framework in PD for elementary teachers, emphasizing its effectiveness in enhancing teachers' ability to incorporate technology into instruction. Through workshops and guided practice, teachers developed instructional units utilizing Web 2.0 tools and mathematical objects, aligning with TPACK principles. The study demonstrated that such professional development initiatives significantly improved teachers' technological, pedagogical, and content knowledge, enabling more effective technology integration in the classroom.

Moreover, recent studies have explored the integration of ChatGPT into educational settings, highlighting both its potential benefits and challenges. A systematic review by Mai et al. (2024) examined the strengths and weaknesses of using ChatGPT in teaching and learning, discussing opportunities and threats associated with its implementation. Additionally, a study conducted by Gill et al. (2024) analysed ChatGPT's capabilities and its impact on the education sector, identifying potential concerns and challenges. These studies collectively suggest that while ChatGPT can enhance personalized learning and provide immediate feedback, there are concerns regarding academic integrity, potential overreliance, and the need for educators to guide its ethical use.

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Bridging The Gaps In STEAM Education: Voices Of Educators

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STEAM education is widely recognised as a key approach for developing 21st-century skills through the integration of science, technology, engineering, arts, and mathematics. However, its implementation remains challenging due to limited resources, insufficient professional development, and weak systemic support for interdisciplinary teaching. This study, conducted within an EU Horizon project, examines the needs of in-service educators through a large-scale mixed-methods survey involving more than 600 participants from more than 25 countries. The analysis focuses on five areas: preparation, implementation, coordination, collaboration, and professional development. The findings highlight financial constraints, lack of preparation time, and limited training opportunities as major barriers. Educators also emphasised the need for real-world learning, improved technological infrastructure, and assessment approaches aligned with interdisciplinary goals. The study points to the importance of policy support, sustained funding, and structured professional development to enable effective and inclusive STEAM education.

Keywords: STEAM Education, Teachers professional development, teacher perceptions

Introduction

STEAM education integrates multiple disciplines to provide learners with a holistic learning experience that supports the development of 21st-century skills. By integrating science, technology, engineering, the arts, and mathematics (STEAM), STEAM promotes inquiry-driven, project-based, and problem-solving learning activities that reflect real-world challenges (Amanova et al., 2025; Leavy et al., 2023). Research shows that interdisciplinary and experiential learning approaches enhance student engagement and better prepare learners for changing labour market and societal demands (Erol, Erol, & Başaran, 2023; Harris & de Bruin, 2017).

The integration of diverse disciplines within STEAM education responds to the growing need for a workforce capable of combining technical knowledge with creativity, critical thinking, and collaboration. Across Europe, industries increasingly seek professionals with strong digital competences, sustainability awareness, and innovation-oriented problem-solving skills (Colucci et al., 2017). In this context, STEAM education plays a key role in supporting future generations to address complex global challenges, including technological transformation and sustainable development (Yeomans et al., 2025; Yim et al., 2025).

Despite its widely recognised benefits, the effective implementation of STEAM education largely depends on educators' ability to design and deliver interdisciplinary teaching (Spyropoulou, Mathiopoulos & Kameas, 2025). This requires not only subject knowledge but also pedagogical approaches that support collaboration across disciplines, real-world learning, and innovative assessment practices (Firmansyah & Aslan, 2025). However, many education systems continue to prioritise traditional, discipline-based structures, limiting opportunities for integrated teaching and learning.

As a result, educators often face structural, organisational, and professional barriers when attempting to implement STEAM approaches in practice (Ariza, J. Á., & Olatunde-Aiyedun, 2023). Limited access to targeted professional development, lack of institutional support, and insufficient time and resources further constrain their capacity to adopt interdisciplinary methods effectively.

This study aims to identify the specific needs and gaps of in-service teachers in relation to the implementation of STEAM education. By examining current challenges in teachers' preparation, support structures, and working conditions, the study provides evidence-based insights to inform strategies that can strengthen STEAM teaching and learning across Europe.

Methods

For this study, we employed a survey-based approach to gather quantitative and qualitative data on the needs of in-service educators in STEAM education. A structured questionnaire was developed to capture various aspects of educators' experiences, competences, and challenges during the different roles of educators during preparing, design, implementing and coordinating STEAM education projects and activities. The questionnaire was designed based on existing research in STEAM education and the competence framework (Spyropoulou & Kameas, 2024). It included demographic questions, Likert-scale items, and open-ended responses to ensure the following five core dimensions:

- Preparation and Development: Understanding of STEAM foundations, curricular standards, disciplinary content, instructional design strategies, and more.
- Implementation: Needs for resources and support to implement pedagogical strategies, content knowledge of specific STEAM disciplines, instructional time, assessment methods, etc.
- Coordination: Support needs for coordinating and managing the educational process, resource and lab management, handling of students/teachers, and school organization/administration.
- Collaboration and Community Building: How to foster cooperation with other educators, institutions, parents, local communities, and industries.
- Professional Development: Understanding of STEAM instructional practices, student motivation strategies, assessment tools, teamwork techniques, classroom organization, and the use of emerging technologies.

The survey targeted 664 in-service educators from 28 countries. The professional roles of participants varied, with secondary teachers comprising the largest group (45.5%), followed by primary teachers (20.7%), secondary principals/directors/education managers (8.5%), and pre-primary teachers (7.0%). Other roles included vocational school teachers and teacher trainers/adult educators. While the overall survey addressed all five dimensions, this paper concentrates on the first dimension, Preparation and Development. This focus enables a detailed examination of the foundational conditions necessary for effective STEAM education and provides insights into the early-stage challenges educators face in designing and planning interdisciplinary learning experiences.

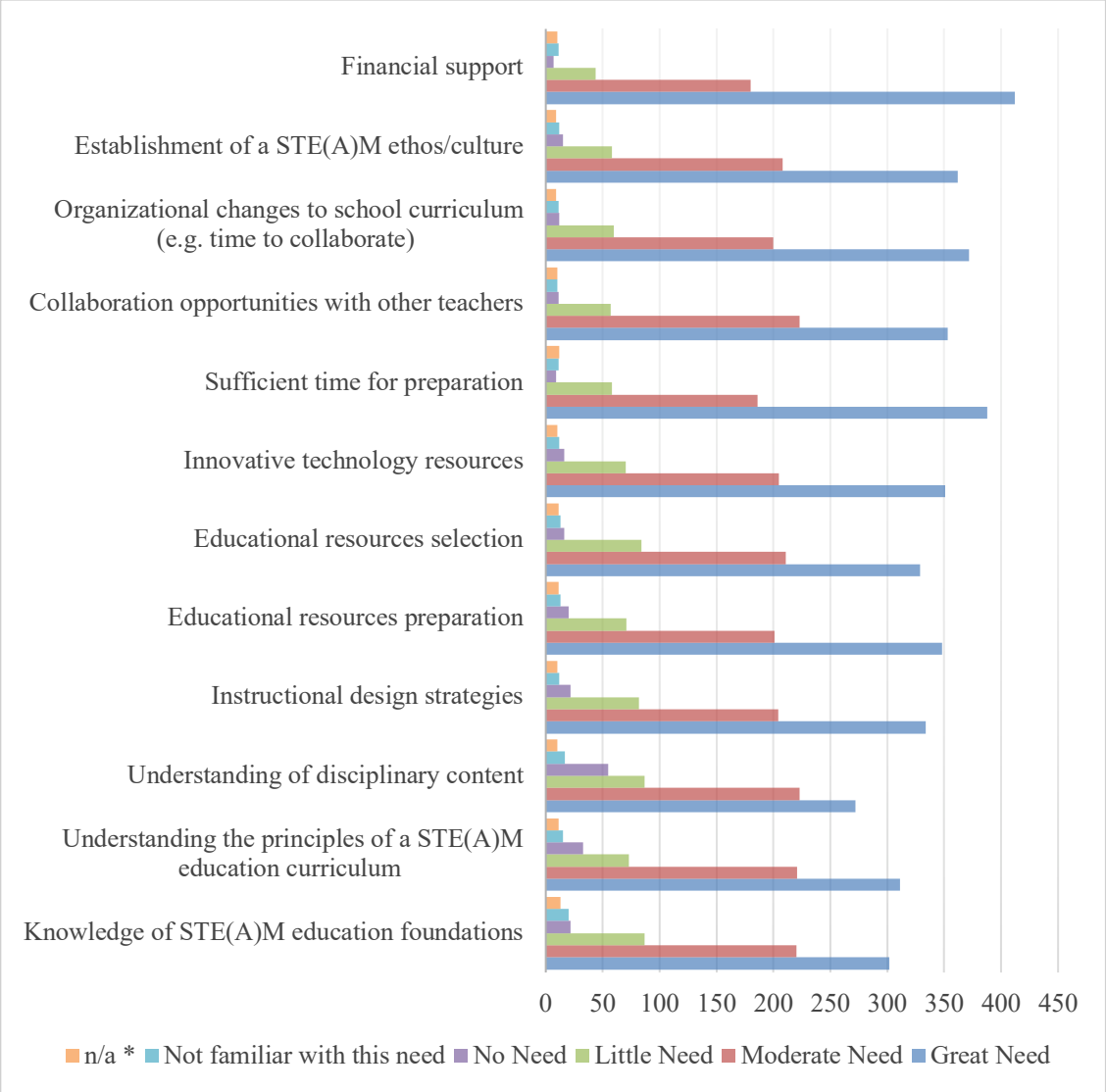
Findings And Discussion

The survey results reveal substantial needs and structural gaps in the preparation and development of STEAM education programmes for in-service teachers. Figure 1 presents an overview of the results for the survey questions. The most prominent finding concerns financial support, which emerged as the highest-ranked need. More than 62% of respondents reported a strong need for funding, while an additional 27% indicated a moderate need. This clearly shows that many schools lack the financial capacity to support teachers and STEAM implementation, including the purchase of materials, technological equipment, laboratory resources, and digital tools.

Closely linked to funding constraints is the issue of time for preparation, which nearly 58% of respondents identified as a major need. STEAM education requires careful planning, coordination across subjects, and the design of interdisciplinary learning activities. The findings indicate that current school schedules do not adequately support these demands, leaving teachers to prepare STEAM activities outside formal working hours. The data also indicate the need for organizational changes within school curricula, with 56% of respondents emphasizing the importance of structural flexibility, underscoring the need for curricular arrangements that enable collaboration, co-teaching, and interdisciplinary planning.

Another important finding relates to the establishment of a STEAM ethos and culture within schools. More than half of respondents indicated that institutional support, shared vision, and leadership commitment are essential for successful STEAM implementation. In addition, teachers reported significant needs related to the preparation of educational resources and access to innovative technologies. More than half of the respondents identified the preparation of STEAM-specific teaching materials and the integration of digital and technological resources as critical. Finally, the development of instructional design strategies tailored to STEAM was identified as a key gap. Teachers expressed the need for guidance on designing interdisciplinary learning activities that align learning objectives, teaching methods, and assessment practices.

Figure 1. Questions result from STEAM educators' needs.



The open-ended responses provided additional insights into the challenges and needs of educators in STEAM education. The thematic analysis revealed four key themes, as outlined in the table below (Table 1):

Table 1. Themes and key findings from open-ended questions.

Theme	Key Findings
Infrastructure and Resources	Lack of modern facilities, need for dedicated STEAM labs, and increased financial support
Curriculum and Assessment	Demand for innovative assessment methods, continuous curriculum feedback
Cultural and Systemic Changes	Resistance to change, calls for reduced bureaucracy, public awareness initiatives
Inclusivity and Accessibility	Need for inclusive learning environments ensuring equal access to STEAM education

Infrastructure and resources emerged as a central concern. Educators frequently referred to the lack of modern facilities, the absence of dedicated STEAM laboratories, and limited access to equipment and digital tools. These constraints were closely linked to insufficient financial support and were seen as a major barrier to implementing hands-on and inquiry-based STEAM activities. Curriculum and assessment challenges were also strongly represented in the responses. Participants highlighted the need for more flexible curricula that support interdisciplinary learning, as well as assessment approaches better aligned with STEAM pedagogy. In particular, educators called for project-based assessment, peer review, and formative feedback mechanisms that reflect collaboration and problem-solving rather than traditional testing practices. A third theme concerned cultural and systemic changes within education systems. Educators reported resistance to change at institutional and administrative levels, alongside excessive bureaucracy that limits innovation. Several respondents stressed the need for stronger leadership support, reduced administrative burden, and broader public awareness initiatives to legitimise and promote STEAM education within schools and communities. Finally, inclusivity and accessibility were identified as critical considerations. Respondents emphasised the importance of inclusive learning environments that ensure equal access to STEAM education for all learners, regardless of gender, socio-economic background, or learning needs. This includes accessible infrastructure, inclusive pedagogical approaches, and targeted support measures to avoid reinforcing existing inequalities.

Discussion And Conclusion

The findings of this study highlight a clear and consistent message: the effective implementation of STEAM education depends on systemic support for educators, extending beyond individual professional development to include financial investment, curriculum flexibility, and strong institutional backing.

Financial support emerged as the most critical need, confirming previous research that identifies funding as a prerequisite for meaningful STEAM implementation (Harris & de Bruin, 2017). STEAM education relies heavily on access to materials, digital tools, laboratories, and flexible learning spaces. Without sustained financial investment, STEAM practices risk remaining

fragmented, project-based, or dependent on short-term initiatives rather than being embedded within school systems.

In parallel, the strong demand for time and professional development reflects broader challenges in teacher preparation and working conditions (Ariza & Olatunde-Aiyedun, 2024). STEAM education requires educators to collaborate across disciplines, design interdisciplinary learning activities, and adopt innovative pedagogical and assessment approaches (Amanova et al., 2025). However, existing school structures often limit opportunities for joint planning and peer learning (Spyropoulou et al., 2025). Consistent with earlier studies, the findings show that targeted professional development, combined with protected time for collaboration, is essential for building educators' interdisciplinary competences and confidence (Conradty & Bogner, 2020).

Rigid subject-based timetables and assessment structures were perceived as major barriers, strengthening the view that STEAM education cannot be effectively implemented without systemic adjustments at the school and policy level (Spyropoulou, Ioannou & Kameas, 2025).

The results also point to curriculum and organisational barriers as major constraints. Rigid subject-based curricula, standardised assessment practices, and limited flexibility in scheduling were perceived as incompatible with interdisciplinary teaching. These findings align with the literature emphasising the need for curriculum innovation and adaptive assessment models to support inquiry-based and project-based learning in STEAM contexts (Shernoff et al., 2017). Addressing these barriers requires policy-level action to allow schools greater autonomy in curriculum design and assessment practices.

Insights from the open-ended responses further illustrate the multifaceted nature of educators' challenges. Infrastructure and resource limitations were repeatedly mentioned, reinforcing the quantitative findings and highlighting the importance of modern learning environments and dedicated STEAM spaces. Educators also called for assessment approaches that better reflect collaboration, creativity, and problem-solving, such as project-based and peer-reviewed methods (Firmansyah, & Aslan, 2025). These findings suggest a mismatch between STEAM pedagogical goals and existing evaluation systems. Cultural and systemic resistance to change emerged as another significant challenge. Educators reported bureaucratic constraints and limited institutional openness to interdisciplinary innovation. Overcoming these barriers requires a cultural shift within education systems, supported by leadership commitment, reduced administrative burden, and increased awareness of the value of STEAM education among policy makers, school leaders, and the wider community. Finally, inclusivity and accessibility were identified as essential dimensions of sustainable STEAM education. Respondents stressed that STEAM initiatives must ensure equal access for all learners, avoiding the reinforcement of existing social, gender, or digital divides. Inclusive pedagogical approaches, accessible infrastructure, and targeted support measures are therefore central to ensuring that STEAM education contributes to both equity and innovation (Weisberg et al., 2025).

In conclusion, the study demonstrates that advancing STEAM education requires coordinated action across multiple levels of the education system. Targeted policy reforms, increased and sustained funding, innovations in curriculum and assessment, and structured professional development are all necessary to support educators effectively. By addressing both structural and cultural barriers, education systems can move towards more inclusive, coherent, and sustainable STEAM learning environments. Such environments are essential for preparing learners to navigate complex societal and technological challenges and to participate actively in an increasingly interdisciplinary and digital world.

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Section: Reflective Practice And Teacher Research In Science Education

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Building Knowledge Together: How Collaborative Professional Development Fostered New Learning Opportunities For Secondary Physics Teachers

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This paper, guided by transformative learning theory, presents how new learning opportunities emerged during three topic-specific collaborative senior physics workshops. We identified structured activities and participant interactions that created opportunities for transformative learning and examined the barriers limiting these opportunities. Using a multiple case study approach, audio recordings during and reflective interviews after the workshops were collected from six participants teaching Year 12 (Grade 11) physics in New Zealand. Qualitative analysis revealed that the CoRe framework's structure and prompts together with the collaborative dialogue created disorienting dilemmas and opportunities for critical reflection, the initial phases of transformative learning. The findings suggest that professional development designed to make teacher thinking visible combined with collaborative conditions that encourage questioning and uncertainty-sharing can systematically create opportunities for transformative learning if teachers have sufficient content knowledge and are willing and ready to engage in alternative perspectives. The study provides facilitators with practical insights for designing collaborative professional learning that may contribute to meaningful shifts in how teachers plan their practice.

Keywords: Physics, Professional Development, Transformative Learning Theory

Introduction

Collaborative Content Representation (CoRe) workshops have been shown to contribute to the development of teachers' pedagogical content knowledge for pre-service and in-service science teachers at both secondary and primary levels (Carpendale, 2018; Eames & Birdsall, 2019; Hume & Berry, 2013; Williams et al., 2012). In these studies, there has been less focus on the specific mechanisms that create learning opportunities within these workshops. Previous studies have instead focussed on learning outcomes, with less exploration of how structured activities and participant interaction created opportunities for learning. This paper examines these approaches through the lens of transformative learning theory (Mezirow, 2003) by answering these questions: How were learning opportunities created in the collaborative-CoRe physics PLD, and in what ways do these learning opportunities align with the initial phases of Mezirow's TLT?

In this study we use "learning opportunities" to refer to moments within the workshops where conditions emerged that could facilitate transformative learning. We focus on opportunities characterised by disorienting dilemmas and critical reflection, the initial phases of Mezirow's transformative learning process. We recognise that while these opportunities create the potential for transformation, whether individual teachers experienced actual transformation in their frames of reference require longer-term investigation that was beyond the scope of this study.

This study focuses on two aspects of TLT: disorienting dilemmas and critical reflection through dialogic interaction. When participants experience disorienting dilemmas, they question their assumptions and consider alternative perspectives. In literature, disorienting dilemmas have been explored in a professional development setting with beginning teachers (Laros & Košinár, 2019) and through the self-reflection of an experienced teacher-educator (Berry, 2010). These studies

show how disorienting dilemmas can disrupt their thinking and act as catalysts for adults to become critically conscious (Mezirow, 1991) and transform their learning.

Critical reflection supports teachers to understand "what they do and why they do it" (Cranton & King, 2003, p. 35). According to Liu (2015), critical reflection incorporates processes (e.g. analysis, questioning), content (e.g. assumptions about teaching), and goals (e.g. improved student outcomes). Despite there not being consensus about whether critical reflection is necessary for new learning, (Fleming, 2018; Mezirow, 2003) it is still one aspect that could lead to transformative practices. Philp-Clark & Grieshaber's (2024) meta-aggregative qualitative evidence synthesis identified that teachers use critical incidents, such as disorienting dilemmas, to reflect and identified that collaborative critical reflection embedded in professional learning and connected to clear objectives appeared to be a successful strategy for supporting a change in teachers' thinking.

Another key aspect of Mezirow's (2003) TLT is the critical role dialogue and dialectic discourse play in learning, which is especially relevant to collaborative professional learning. Mezirow emphasises that transformative learning occurs through dialectic dialogue, where adults critically examine their assumptions and engage with alternative perspectives. Richman et al. (2019) claimed that collaborative professional learning can facilitate changes to science teachers' practice with the New Generation Science Standards. Similarly, while not at secondary level, Nolan and Molla (2018) demonstrated that early childhood teachers learn best when they engage in thorough and thoughtful analysis through social collaboration, suggesting that this collaborative approach may be beneficial for teachers regardless of age groups taught.

Method

This qualitative study employed a multiple case study approach to examine how new learning opportunities occurred during collaborative professional learning. The design was useful because it enabled us to explore deeply how teachers created opportunities for new learning through dialogue in their experiences of disorienting dilemmas. Full ethical approval was obtained from the Human Ethics Committee at Victoria University of Wellington (VUW) (0000030762), and the research process was conducted in accordance with the NZARE (2010) guidelines.

Six fully informed and consenting participants teaching senior physics in New Zealand participated in this study. All participants had more than five years of teaching experience and worked in English-medium schools following New Zealand's national curriculum. Their schools represented diverse socio-economic backgrounds. Participants were recruited through convenience sampling, replying to an email seeking expressions of interest.

Three audio recordings and six interviews were analysed using Johnson and Christensen's (2020) analytical approach. First, it was transcribed before being segmented during preliminary reading. Deductive coding identified instances of learning opportunities, and inductive coding identified patterns in the new learning opportunities and themes were created. A hierarchical coding system and network diagram helped us to explore the relationships between the codes and themes. Intercoder reliability checks were completed once themes had been established and themes were linked to specific approaches of TLT.

The study centred around three four-hour workshops based on Loughran et al.'s (2008) Content Representations (CoRe) which were operationalised in collaborative settings for pre-service secondary chemistry teachers (Hume & Berry, 2011, 2013) and in-service secondary science (Carpendale & Hume, 2020; Eames & Birdsall, 2019) and primary science teachers (Hume, 2016). The workshop utilised a bottom-up approach (Timperley, 2011) to develop individuals' teaching and learning knowledge and skills related, in this study, to a physics topic. The

workshops aligned with the participants' upcoming physics topic, the New Zealand Curriculum (Ministry of Education, 2007), and the relevant Physics Achievement Standards from the New Zealand Qualifications Authority (NZQA, 2014a, 2014b, 2014c). Participants met in groups of between two and four to collaboratively create a CoRe-design. They identified the key concepts and big ideas in the topic and, using the prompts discussed for each big idea, the importance of the concepts, the teaching strategies, the difficulties, misconceptions, and associated models and representations that could be used to teach the big ideas, and strategies to assess the big ideas.

Teachers attended between one and two workshops which were spaced two months apart. This spacing reflected the need to schedule topics before teachers began teaching them. They were facilitated by the first author, an experienced physics teacher, who intentionally avoided providing content explanations. Direct facilitator interventions offering content support or pedagogical solutions were excluded from the data analysis, however, procedural facilitation was included as this formed part of the workshop structure and did not pre-determine participant responses. The semi-structured one-on-one interviews exploring teachers' perceptions of learning, reflections of changes in their thinking about physics content and pedagogy were completed within two weeks of the workshops and lasted between 45 and 60 minutes, these were conducted in person or online by the first author.

Results And Discussion

Structure and Prompts

Opportunities for new learning occurred when teachers articulated their uncertainty into a shared space which allowed others to offer alternate perspectives. The structure and prompts of CoRe seemed to support teachers to discuss topic-level PCK in a more nuanced way than when they first considered it. This progression can be identified in the following example. Initially teachers' thoughts around assessment were relatively undifferentiated.

> P1: "Assessments for different concepts, we can just put the same approach can't we?"
>
> P2: "I mean just walking around and asking students about the work"
>
> P3: "Really? Like what, more quizzes?"

After further exploration of the big ideas through the CoRe prompts, one teacher articulated a more sophisticated understanding of assessment:

> I'll still go round and talk to students and ask them questions, but actually, you could build circuits and get students to check their understanding with me… That way they start to understand some of the practical [skills], concepts, and how they go together.

This shift towards a more nuanced understanding suggests that the prompts and structure of the CoRe contributed to deepening this teachers' understanding of assessment strategies in this topic.

The collaborative aspect supported by CoRe prompts appeared to encourage teachers to experience disorienting dilemmas. Sorting key concepts into groups provided opportunities for teachers to question and disagree with each other, which served as a productive tool for deepening their understanding. In the following example, three teachers explored what "nuclear stability" meant to them and whether it is an appropriate term to use.

> P1: "we have atomic structure, so could another big idea be nuclear stability?"
>
> P2: "what do you mean by stability and why would you use it?"
>
> P1: "because those are released when we undergo nuclear decay."

P2: "Does that make it more stable? … for me this is not stability, because it just goes ting, ting, ting, ting, ting (indicates transformation of atomic nuclear by decay)…

P3: "are you looking at the fundamental forces when you mean stability?""

P1: "some atoms are more stable than others… in using the term 'stability' I'm describing a measure of how stable a particular atom is… The forces are a bit beyond what is needed I think.

P3: Those are covered at year 13, perhaps we could use reaction.

P1: Stability is good for half-life though

P2: I think you're talking about two different things. We should look at each idea first before grouping them.

Through these interactions, P1's initial vague notion of nuclear stability was challenged and refined. P2's questioning revealed a conceptual ambiguity which resulted in the group collectively recognising that they needed to clarify the individual concepts thoroughly before organising them. When multiple interpretations were shared and disagreement created, participants were able to experience disorienting dilemmas.

The structure of the collaborative CoRe also encouraged opportunities for critical reflection. When discussing why it was important to teach and understand the history of the atom, the teachers initially began with surface level justifications, including "teaching vocabulary" and "it's required content." When the facilitator contextualised one of the prompts, "why is it important to know about this general atomic model changes over time?", one teacher began to examine their underlying assumption that they "teach it because I'm required to" and recognised this framing as problematic to students' deep understanding of science as an ever changing body of knowledge and appeared to shift her perspective.

> The biggest thing for me is that they need to realise that when I start with an atom, I'm like 'ohh this is an atom, the nucleus is in middle and electrons outside,' but now this is not how it looks like anymore. Then they go, 'why didn't we learn that in year 9?'. That [progression] is helpful as it shows them that ideas change, and this change is because of technology and changes over time.

Building on this insight, a second teacher extended this critical reflection by suggesting another historical example from different scientific domains to demonstrate how scientific understanding evolves and highlighting the importance of students gaining this epistemological understanding of science: "if you can get access to the medical texts from the 16th century. [you'd see] 'He has a headache, so we're going to drill a hole into his head through his skull to relieve the pressure.'" This example illustrated the teachers understanding that the history of atomic models helps students see science not as a collection of facts, but as a field where mistakes have been made and corrected, making it important to learn from past errors and essential for developing students' critical awareness.

This example illustrates Mezirow's (1981, 2003) concept of critical reflection in action and demonstrates how the CoRe prompts facilitated critical reflection which then contributed to transform teachers' understanding from viewing content as something that needs to be covered to recognising its role in developing students' epistemological understanding of science.

Barriers To Learning

Two barriers were identified that did not appear to encourage these opportunities to be created. The first, was teachers' self-reported understanding of the content and concepts being taught in

the topics. These included one teacher who was new to teaching physics and suggested he "didn't have enough content knowledge." This teacher reported being "a passive observer," did not participate a lot in discussions, and reported during workshops that "this is just going over my head." This teacher was sometimes dismissive of other teachers' desire to explore concepts in more detail stating, "kids' don't need that" and "do we want to make physics boring for them?" Another teacher also made minimal contributions in some sections, they reported during the workshop and in the follow up interview that "to be honest I don't know a lot about it." Discussions about concepts and pedagogy were unable to progress when teachers were unable to participate or explain more fully.

The second barrier identified was teachers' willingness or unwillingness to consider alternative approaches and ideas. Beyond the teachers already identified, a third teacher demonstrated an unwillingness to engage with alternative perspectives. They expressed boredom "I'm so bored… I feel like we're trudging through the same thing again," showed resistance to probing concepts further "I hadn't intended to [discuss fundamental forces], do you [the facilitator] want us to?" and were content with their teaching methods "for level 2 I just have a booklet that I made and the students go through the booklet. it's the same each year… and I know it works because I wrote it." These types of interactions not only reduced their own opportunities to engage with new ideas but also other teachers' opportunities to explore new concepts and approaches.

These instances showcase how teachers' content knowledge limitations and unwillingness to engage not only reduced their participation in the conversations but also appeared to reduce the chances of them experiencing disorienting dilemmas and critical reflection. Whether these conversations created an opportunity for these processes to occur internally was not captured in the data and cannot be discounted. The evidence, however, suggests that for transformative learning to occur, teachers need both sufficient content knowledge to recognise challenges to their existing frameworks and an openness to engage with alternative perspectives. It should be noted though, that these less open-minded behaviours not only did not progress conversations for others, but may have deterred others sharing when the comments seemed dismissive. These barriers emerged despite the facilitators' repeated attempts to prompt reflection and create opportunities for deeper engagement, suggesting that structural factors alone, such as collaborative time and prompting questions, may be insufficient when teachers lack content knowledge or appear unwilling to engage in learning.

Discussion

This study demonstrates that structured collaborative professional development can systematically create the conditions for transformative learning as described by Mezirow's theory (2003). The CoRe framework's prompts and collaborative structure facilitated the initial phases of transformative learning: disorienting dilemmas and critical reflection, by creating spaces where teachers were able to articulate their uncertainties and experience alternative perspectives through discussion. When teachers engaged in productive disagreement, they were prompted to reconsider their understanding when other teachers challenged their ideas and assumptions. Similarly prompts pushed teachers beyond surface-level responses and allowed them to examine their underlying pedagogical assumptions and shift their thinking. These findings align with previous research showing how disorienting dilemmas can catalyse transformative learning in professional development settings (Berry, 2010; Laros & Košinár, 201) and support Philip-Clark and Grieshaber's (2024) conclusion that collaborative critical reflection that is embedded in professional development can contribute to changing teachers' thinking.

Fewer opportunities for new learning were identified for teachers with limited content knowledge. Mezirow (2003) defined transformative learning as "learning that transforms

problematic frames of reference" to make them "more inclusive, discriminating, open, reflective, and emotionally able to change" (p. 58). For transformation to occur, adults must first have an existing frame of reference that can be challenged. Teachers who lacked experience teaching the content and confidence in their content knowledge may not have yet established conceptual and teaching frameworks for the topics behind discussed that could be disrupted or transformed. This finding suggests that transformative learning opportunities may be inappropriate for teachers in the early stages of developing their content knowledge or pedagogical content knowledge. Instead, of this collaborative approach, they may require professional learning that focusses on acquiring new knowledge and skills rather than transforming existing perspectives. Furthermore, the "not knowing" about content prevented teachers from engaging in what Mezirow describes as "critical dielectric discourse involving the assessment of assumptions and expectations supported by beliefs, values, and feelings" (p. 60). In these cases, it appeared the teachers had not yet formed assumptions about what these concepts were and how to teach them.

Teachers' dispositions did not sometimes appear to suit to this type of professional learning. Mezirow (2003) emphasises that participating in critical dialectical discourse requires "having an open mind, learning to listen empathetically, 'bracketing' premature judgement, and seeking common ground" (p. 60) as well as emotional intelligence including "empathy and social deftness" (p. 60). Participants who were unwilling seemed resistant to exploring deeper, appeared satisfied with their existing understanding of concepts and practices, which suggests they held a frame of reference that was not "open, reflective, and emotionally able to change" (p. 58). Despite having access to potential disorienting dilemmas, such as the debate about nuclear stability, this teacher appeared to actively avoid engaging with these challenges, suggesting they were not actively engaging in learning.

Whether these conversations that are supported by the CoRe framework created opportunities for internal disorienting dilemmas and critical reflection that were not verbalised could not be discounted. Mezirow (2003) states that adult educator's role is "to help learners acquire the skills, sensitivities, and understandings essential to become critically reflective of assumptions and to participate more fully and freely in critical-dialectical discourse" (p. 62). This assumes that providing such help will be effective, and that learners are willing and able to develop these capacities. These findings challenge this assumption and reveal that transformative learning requires both sufficient content knowledge as well as a dispositional openness to engage with alternative perspectives. When these prerequisites are not present, even appropriate facilitation and structures may not be sufficient to create conditions for transformative learning. Furthermore, in collaborative professional learning settings, individual resistance may compromise the conditions required for discourse for themselves and other group members.

Conclusion

To create learning opportunities that support transformative learning, these findings suggest PLD providers consider including structured activities where teachers are required to make their thinking visible, create collaborative conditions where teachers feel comfortable sharing uncertainties and questioning their teaching practice to enable authentic dialogue, and find strategies to identify whether teachers are ready to learn, both with their content knowledge and dispositions. While the study provides insight into collaborative professional development, several limitations exist. The small sample size, while useful for gathering rich and in-depth data, limits generalisability. Additional limitations include potential researcher bias due to the facilitator also being the primary researcher. While this provided deep insight into workshop dynamics, it may have influenced both the facilitation approach and data interpretation. We attempted to mitigate this through reflexive journalling, intercoder reliability, and member

checking. Additionally, whether this approach can be used in other subject areas or cultural contexts requires further research, given the focus on senior physics and a New Zealand setting. Further research might explore how this approach transfers to other subject areas and whether the effectiveness persists in longitudinal studies that track sustained changes in teaching practices.

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Development Of Teacher Training Model That Transforms The Science Teacher Competencies

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This study aims to develop a professional learning model based on lesson study as a form of on-the-job training (OJT). It responds to the current situation in Japan, where teachers have difficulty participating in professional development outside of working hours. Teacher competencies were conceptualized as Competency in Mind (CM), which appears in teachers' conscious awareness, and Competency in Action (CA), which appears in their behaviors during lesson study. The study examined the process through which these competencies transform, based on the relationship between CM and CA. As a theoretical framework, Naumescu's (2008) GPC (Good Practices related on Competencies) and Kiper & Mischke's (2009) Structural Theory of Instruction were adopted. The GPC items were reclassified into three categories—TTC (Teacher–Teacher), TSC (Teacher–Student), and TCC (Teacher–Context)—and used for analysis.

A qualitative study was conducted with one science teacher (Mitsuzane), using a combination of the GPC questionnaire (for CM) and utterance analysis during lesson study (for CA). Prior to the lesson study, the teacher received feedback on his CM profile to enhance awareness of his competency tendencies. The researchers then examined changes in CA during the lesson study. Afterward, interviews were conducted to explore the gaps between CM and CA. Results showed that the teacher made conscious efforts to improve GPC items that had been rated low in his CM. Actual improvement in CA—particularly within the TCC domain—was also confirmed. Notably, GPC items related to classroom management and the analysis of students' responses were prominently manifested in CA. These items had been rated low in CM. The teacher also stated that the prior presentation of CM influenced his actions during lesson study. This suggests that CM awareness may foster intrinsic motivation for learning and may lead to behavioral transformation.

Analyses with three additional teachers indicated that researchers' recommendations contributed to changes in CA. This further supports the influence of targeted guidance. The significance of this study lies in showing that incorporating a CM-awareness process into lesson study can establish an effective learning model. This model enables teachers to enhance their competencies autonomously.

Keywords: Teacher Competencies, Lesson Study, Professional Learning

Introduction

According to TALIS 2018, Japanese elementary and lower secondary teachers spent the least amount of time on professional development among all participating countries. This limited participation was attributed to factors such as scheduling conflicts and responsibilities at home.

In Tokyo, professional development is described as comprising three modalities: on-the-job training (OJT), off-the-job training (Off-JT), and self-directed learning. OJT refers to professional learning that takes place within the school, grounded in concrete situations and teacher actions. Off-JT includes group or online training organized by boards of education and dispatch programs to professional graduate schools of teaching. Self-directed learning refers to voluntary professional learning such as reading books and attending seminars. In other words, the TALIS

2018 results suggest that Japanese teachers face difficulties allocating time for Off-JT or self-directed learning. The same survey also found that many Japanese teachers viewed professional learning in instructional methods and content knowledge more positively when others observed their lessons and provided feedback.

Given this context, professional development that is feasible for Japanese teachers is that which can be conducted during working hours as OJT. To enhance competencies related to instructional methods and content knowledge, it is necessary to create a professional learning environment in which teachers' classroom instruction is observed by others and feedback is provided.

In Japan, lesson study has long been practiced as one form of professional development. According to Isozaki (2015), lesson study consists of the following:

> Lesson study aims to improve teachers' instructional expertise and build collegiality through collaborative engagement among teachers. It is divided into three stages: the planning stage, the implementation stage, and the reflection stage.
>
> In the planning stage, teachers collaboratively identify issues of concern and decide on the research theme, learning goals, and lesson plan. They also determine the lesson content, instructional focus, materials, and assessments. These planned activities serve as concrete indicators that clarify the value of lesson study for both the teacher conducting the lesson and the observers.
>
> During the implementation stage, observers evaluate the lesson using the lesson plan as a guide. They collect data related to learning goals and focal activities, record observations, and attend carefully to the utterances of teachers and students to interpret their understanding of the content. In science classes involving hands-on activities such as experiments, observers may also examine motor-skill aspects or move around the classroom to capture the learning status of specific students. Japanese lessons often follow an inquiry-based learning process consisting of problem setting, information gathering, analysis, and synthesis. Lessons may also be recorded for later analysis.
>
> During the reflection stage, immediately after the lesson, teachers, observers, and invited experts review the lesson based on the collected data. The results of these discussions—both strengths and challenges—are accumulated and often compiled into a research report at the end of the study period. A research presentation meeting may also be held, showcasing the lesson and its outcomes and featuring a lecture by an invited expert.

However, in recent years, lesson study in Japan has been deteriorating due to the severe worsening of teachers' working conditions. TALIS 2024 also reported that Japan had the lowest ratings worldwide on items such as "All in all, I am satisfied with my job," "If I could decide again, I would still choose to work as a teacher," "I enjoy working at this school," and "I would recommend this school as a good place to work." Therefore, this paper seeks to reconstruct lesson study as a method of professional development. This study develops a professional learning model through lesson study to enhance science teachers' competencies and to cultivate teachers who are deeply aware of the noble mission of their profession, who continuously engage in inquiry and self-cultivation, and who strive to faithfully fulfil their professional responsibilities.

Theoretical Framework

This section summarizes prior studies that form the theoretical background of the present paper. Before explaining the theoretical background, Table 1 summarizes the key concepts and abbreviations used in this paper.

Table 1. Key Concepts and Abbreviations

Abbreviation	Full Term	Definition / Explanation
CM	Competency in Mind	Competencies consciously recognized by teachers, measured through the GPC questionnaire.
CA	Competency in Action	Competencies manifested in teachers' behaviors during lesson study.
GPC	Good practices related on competencies	Framework by Naumescu (2008) consisting of 28 competency items used for analysis.
TTC	Teacher–Teacher Competencies	GPC items related to teachers' knowledge, epistemological understanding, and interactions with colleagues.
TSC	Teacher–Student Competencies	GPC items related to teaching–learning processes and interactions with students.
TCC	Teacher–Context Competencies	GPC items related to managing instructional contexts, classroom situations, and contextual factors.
LPM	Lesson Planning Map	Framework adapted from Kiper & Mischke (2009) to analyse teacher competencies across planning, implementation, and evaluation stages.

GPC: Good Practices Related On Competencies

In Japan, no competency framework specifically defines the professional competencies required of science teachers. Therefore, we attempted to apply Naumescu's (2008) "Good Practices related on Competencies (GPC)" to Japanese science teachers (Table 2). Conventional competency frameworks generally focus on qualities derived from knowledge of scientific concepts. In contrast, GPC assumes actual classroom situations and therefore includes competencies related to managing instructional contexts—an essential aspect of science teaching. This study investigates how competencies transform through lesson study. Therefore, we focused on Naumescu's 28 GPC items and examined their applicability to Japanese science teachers.

Table 2. Good practices related on competencies (Naumescu, 2008).

Competence in epistemology
- Epistemological competence on models building, on processes of the students' modelisation, and on the functions and limits of each model.
- Competence in the use of technical and scientific apparatus and engineering.
- Competence to define criteria of categorisation (an important process in different scientific domains, as taxonomy, DNA sequences, …)

- Competence on the history and limits of validity of each scientific concept, and on the social dimension of the science.
- Ability to differentiate a scientific proposition to a non-scientific one.
- Ability to differentiate a scientific discourse to a dogmatic one.

Competence in bibliography

- Competence to use internet, CD-Rom, books library, etc.
- Competence for a critical analysis of documents of science popularisation (journals, magazines, books, radio, TV, etc.)

Competence in Science Education (Didactics of Sciences)

- Analysis of learners' conceptions on a scientific topic, before teaching this topic, and after this teaching to evaluate the eventual conceptual changes.
- Use the learners' errors not to judge them but as conceptions to be analysed and then changed.
- Identification of epistemological (and didactical) obstacles, to define new strategies of teaching focused on these obstacles
- Building of didactical situations adapted to learning. For instance, problem based situations, or projects (to realise individually or by little groups).
- In particular, sequences to learn scientific concepts, and / or scientific processes (laboratories).
- Competence to define the didactical contract and the situation to the learners, and to present them to learners as a space of active autonomy for them.

Competence in Didactics of Sciences and in Pedagogy

- Competence to induce the devolution of this situation by the learners: they must be motivated to be active in this situation. They have to be implied in the choice of their topics and activities.
- Competence to manage the situation, to improve debates and socio-cognitive conflicts.
- Competence to hear the pupils and students, and to take into account their questions.
- Competence to manage problems of violence, disorder and other difficulties in the classroom.
- Competence to analyse his or her own reactions (psychology) and the students' ones.
- Competence of the teachers to analyse their own reactions in these situations; to manage students' practical, theoretical or speculative works.

- Competence to analyse the scientific background of each student activity and to help them to find these theoretical pre-required.

Competence in didactical transposition and use of language
- Adaptation of the scientific language in a language adapted to children; idem for the images (didactic transposition for each scholar level). - For each scientific notion, proposition of a progression of teaching – learning sequences, in respect with different students' ways and speed of learning. - Use of good metaphor, examples and other pedagogical strategies. - Competence to motivate and help students to write reports on their activities.
Competence in Evaluation
- Competence to imagine processes of analysis and validation of the students works, of their hypotheses and conjectures. - Competence to do evaluation of the students activities at different steps of their work, to help them in their learning and to prepare them for the final evaluation. - Competence for a final evaluation on known criteria, if possible avoiding the "by heart learning", and corresponding to acquisitions of the taught competencies.

In this study, teachers' utterances during lesson study were analysed to identify competencies. Specifically, each utterance was examined to determine which GPC item it corresponded to. The "interaction target" was categorized as Teacher, Student, or Context (Naumescu, 2008). Based on these interaction types and the nature of the competency, the 28 GPC items were reclassified into three categories, namely TTC (Teacher–Teacher Competencies), TSC (Teacher–Student Competencies), and TCC (Teacher–Context Competencies).

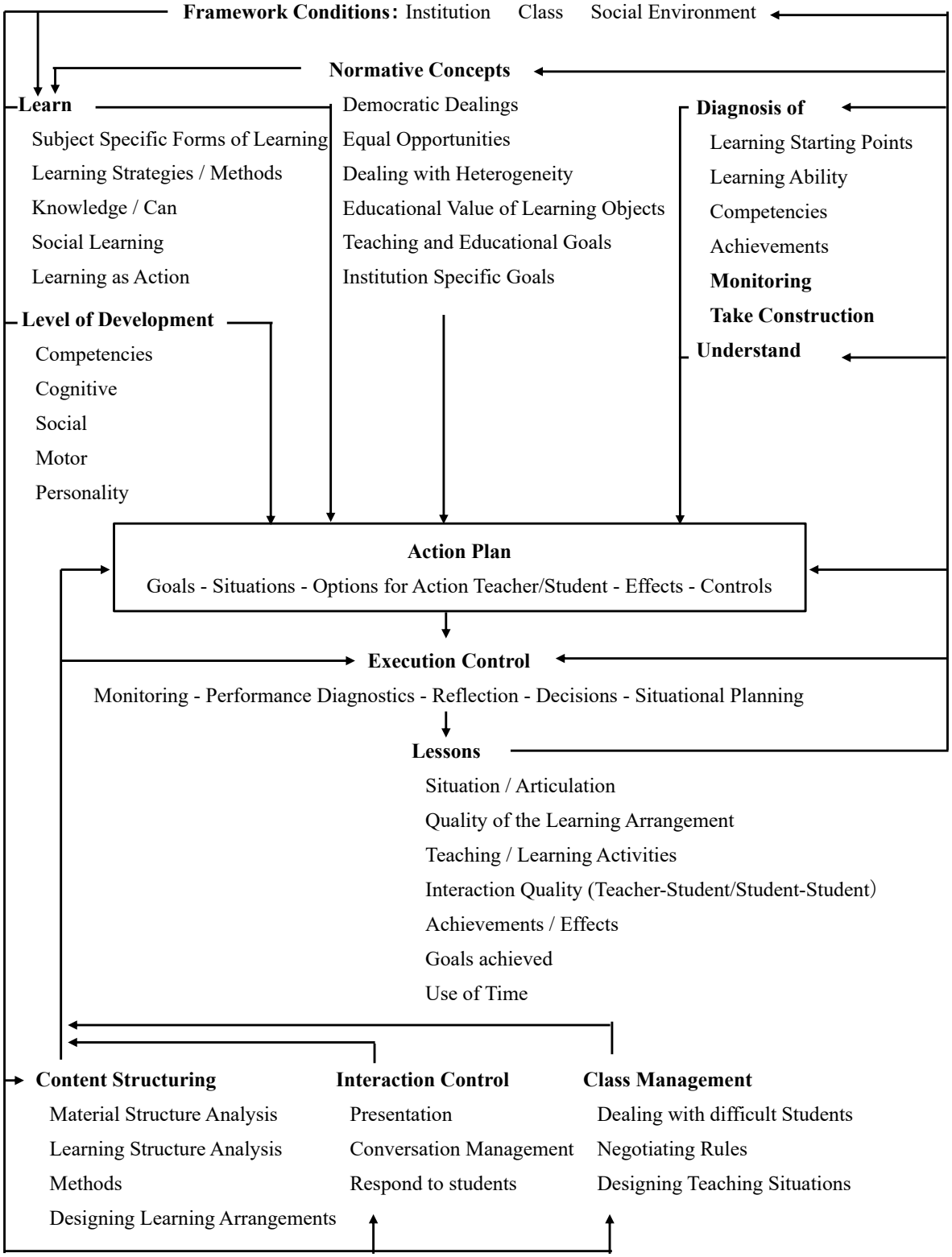
A questionnaire survey using the GPC framework was administered to 135 elementary and lower secondary science teachers in Tokyo. Using a seven-point Likert scale, teachers rated the degree to which they believed each item should be considered an essential science teacher competency. Results showed positive evaluations across all 28 items, indicating that GPC was accepted by Tokyo's science teachers as a valid competency framework.

Further analysis examined correlations among the three GPC categories. Pearson's correlation coefficients revealed strong positive relationships between TSC and TTC ($r = .75$) and between TSC and TCC ($r = .86$). This suggests that Tokyo teachers primarily conceptualize competencies with a focus on interactions with students—namely, TSC.

LPM: Lesson Planning Map

Japan lacks a theoretical model for analysing lesson study. Therefore, we drew on Kiper & Mischke's (2009) Structural Theory of Instruction (Figure 1). In this theory, instructional practice is conceptualized as a cyclical route map consisting of a planning stage, an implementation stage, and an evaluation stage—an idea consistent with Japanese lesson study. We adapted this theory into a lesson-study framework and named it the Lesson Planning Map (LPM).

Figure 1. Structural Theory of Instruction (Kiper & Mischke, 2009).



In this model, teacher utterances from the planning, implementation, and evaluation stages are recorded. In the planning and evaluation stages, interactions occur mainly with colleagues and facilitators; in the implementation stage, interactions occur with students. Recorded utterances are transcribed, and multiple researchers determined whether each sentence corresponds to a GPC item. Then, each utterance is mapped onto the appropriate LPM element according to the stage of lesson study in which it occurred. GPC items, categorized into TTC, TSC, and TCC, are tallied, and these counts are summarized in a table along with GPC questionnaire results.

CM: Competency In Mind And CA: Competency In Action

When comparing a teacher's TTC, TSC, and TCC scores, one may notice distinctive patterns in mean values and frequencies of utterances. These patterns represent the teacher's competency tendencies. Moreover, comparing GPC results from questionnaire data and lesson-study utterances reveals discrepancies (gaps) between mean scores and actual utterance frequencies. These gaps indicate differences between competencies recognized consciously and competencies manifested in practice.

Hokari & Wada (2025a) defined CM (Competency in Mind) as the competencies reflected in a teacher's conscious awareness, as revealed through questionnaire responses, and CA (Competency in Action) as the competencies expressed through actions during lesson study. A gap between CM and CA may indicate competencies that teachers believe they possess but do not exhibit during lesson study, or conversely, competencies that teachers do not consciously recognize but nevertheless demonstrate in practice.

Research Questions

The theoretical framework discussed above has been clarified in Hokari & Wada (2024) and Hokari & Wada (2025b). To further advance this line of inquiry, the present study addresses the following research questions:

RQ1: When teachers are explicitly informed of their CM prior to lesson study, do they attempt to autonomously transform their competencies through the lesson study process?

RQ2: Does teachers' intention to transform their competencies influence their CA?

Methods

This study adopts a qualitative research approach based on questionnaire data and interviews. Using the GPC questionnaire results, the researcher first presented the teacher's CM tendencies to promote self-awareness. In this study, "utterances" refer to all verbal statements produced by teachers during the planning, implementation, and reflection stages of lesson study. Each utterance was treated as a unit of analysis and coded according to the corresponding GPC item. If a teacher expressed multiple ideas in a single turn, these were segmented into separate utterances. The teacher's utterances during lesson study were then analysed to capture changes in CA. After comparing CM and CA, the researcher provided feedback and conducted an interview to explore the observed gaps.

The participant in this study was one teacher, referred to as Mitsuzane (a pseudonym). He holds a bachelor's degree in science education and has worked as a public elementary school teacher for more than 20 years. He has participated in over 26 science lesson studies. At the time of the study, he was teaching a fifth-grade class. The participant had a prior professional relationship with the researchers, which was disclosed to the institution and managed appropriately.

The lesson study analysed in this research was conducted within a district-level research group of science teachers from 29 public elementary schools under the same municipality. The group conducts two to three lesson studies annually, and one of these was selected for analysis. In Japan, the fifth-grade science curriculum includes learning about the flow of rivers—specifically, that flowing water erodes land, transports and deposits stones and soil, that the size and shape of riverbed stones differ between upstream and downstream regions, and that rainfall affects the speed and volume of flow and can cause significant changes to landforms. The present study focused on a lesson within this unit on flowing water. This unit was selected because novice

teachers often report difficulty in conducting science lessons on this topic, making it a meaningful context for examining how teacher competencies transform during lesson study.

Before the lesson study, the researchers identified Mitsuzane's CM tendencies and provided suggestions for improving his GPC in relation to the target unit. After the lesson study, the teacher's utterances were analysed by two researchers to determine which GPC items appeared and at which elements of the LPM these utterances were produced. Based on these analytical results, an interview was conducted to explore the gap between CM and CA. All utterances during the lesson study were recorded using a tablet device. Written consent was obtained from all participating teachers and students after explaining the research purpose and procedure.

Results

The results of the GPC questionnaire for the participating teacher showed mean scores of 5.5 for TTC, 5.3 for TSC, and 4.8 for TCC (Table 3). This indicates that the teacher's CM reflected relatively lower awareness of GPC items related to interactions with the context.

Table 3. Mitsuzane's GPC Profile.

	TTC	TSC	TCC
GPC for Questionnaire Survey	5.5	5.3	4.8
GPC for Lesson Study	32	30	31
Framework Conditions	0	0	1
Normative Concepts	1	0	0
Learn	1	0	1
Level of Development	1	0	1
Content Structuring	7	2	1
Interaction Control	0	0	0
Class Management	0	0	0
Action Plan	0	0	0
Execution Control	3	13	4
Lessons	8	9	12
Diagnosis	8	5	10
Understand	3	1	1

Prior to the lesson study, the researcher provided concrete suggestions to the teacher about how GPC related to interactions with the context could be transformed in the unit on flowing water.

> **Researcher:** Among the TCC competencies, one that did not appear strongly in your CM was "Competence to manage problems of violence, disorder and other difficulties in the

classroom." Perhaps you have had few experiences teaching in challenging class environments?

Mitsuzane: No, I think I do have experience. I have often been in charge of classes that were considered difficult to manage.

Researcher: I see. In that case, although you have experience, it appears that you do not regard this as an essential competency for science teachers. In other words, you may be perceiving that classroom management is not necessary for effective science instruction.

Mitsuzane: That's not the case. But I agree there may be a discrepancy between the numerical results and my self-perception of my teaching practices. So I'm curious to see what my CA will look like.

Researcher: Another GPC within TCC that appeared weak in your CM was "Competence to analyse his or her own reactions (psychology) and the students' ones." This suggests that you may not be frequently anticipating students' reactions before lessons, nor analysing them afterward.

Mitsuzane: That's certainly true. I don't do that very often.

Researcher: For example, during the post-lesson discussion, if you are able to say things like, "I intended to do this in the lesson, but since the students responded in this way, I adjusted my approach," such exchanges could help transform this GPC through CA.

Next, the analytical results of the lesson study (CA) were fed back to the teacher, and interviews were conducted to determine whether changes in GPC were related to the teacher's awareness of CM prior to the lesson study.

Researcher: Analysis of the GPC that appeared during lesson study revealed 32 instances of TTC, 30 of TSC, and 31 of TCC. Unlike your CM, your CA did not indicate a weak awareness of TCC. To be more specific, the TCC item "Competence to manage problems of violence, disorder, and other difficulties in the classroom" emerged 12 times during the implementation stage in CA. This occurred despite the item being rated low in CM. For example, before each experiment, you paused all student activity and provided clear instructions. You also verified students' self-designed experimental procedures before allowing them to continue. When a student reprimanded another for talking, you intervened and clarified that classroom discipline is the teacher's responsibility. These behaviors demonstrate clear articulation of class norms and effective classroom management. This was evident in your CA. Similarly, "Competence to analyse his or her own reactions (psychology) and the students' ones" was rated low in CM but was observed 10 times during the evaluation stage in CA. You frequently commented on how you adapted your instruction based on students' responses. Through this analysis of your CA, we were able to gain a clearer understanding of your TCC.

Mitsuzane: Wow, that's surprising. But hearing this analysis, I see your point. I've conducted many lesson studies, and I recognize that I still have weak GPC areas. I now realize that gaps in my own GPC may be connected to areas where I am not fully fostering students' competencies.

Researcher: There were 93 total GPC-related utterances. This is high relative to previous studies that used similar analyses. In other words, the large number of GPC manifestations suggests that the science teacher's competencies you already possess are relatively advanced.

Mitsuzane: Thank you.

Researcher: Do you think receiving information about your CM before the lesson study—and being asked to anticipate how weak areas might emerge in this unit—had any influence on your CA?

Mitsuzane: When I was told that certain GPC scores were low based on the questionnaire, I felt that there must be something lacking in me. So I made a conscious effort to focus on those areas during the lesson study. Although I do not believe that I neglect those competencies in my everyday teaching, having them pointed out numerically made me think that I may be weaker than I had realized. So I reflected on those GPC during my daily lessons as well.

Researcher: Which GPC stayed in your mind most strongly?

Mitsuzane: The TCC item, "Competence to analyse his or her own reactions (psychology) and the students' ones." When it was pointed out, I thought it might indeed be one of my challenges. So yes, discussing my CM before the lesson study definitely shaped my CA.

As Mitsuzane stated, "I made a conscious effort to focus on those areas during the lesson study." This directly answers Research Question 1: When teachers are informed of their CM prior to lesson study, do they attempt to autonomously transform their competencies? Furthermore, Mitsuzane's comment that "discussing my CM before the lesson study definitely shaped my CA" answers Research Question 2: Does a teacher's intention to transform competencies influence CA?

Discussion And Conclusions

The names Furuichi, Wada, and Miyauchi are pseudonyms used to protect the participants' identities. This study demonstrates that providing teachers with their CM prior to lesson study can enhance their awareness of professional competencies and promote autonomous behavioral transformation during lesson study. Moreover, the findings indicate that teachers' intention to improve their competencies plays a significant role in shaping their CA. This intention was evident in the teacher's explicit statements during the interview, in which he reported consciously focusing on areas identified as weak in his CM. These conclusions are supported by the interview results showing that teachers consciously attempted to work on competency areas identified as weak in their CM. The same pattern was confirmed with three additional teachers, suggesting that CM awareness and targeted recommendations may consistently contribute to changes in CA (Table 4).

Furuichi previously worked as a lower secondary science teacher and holds specialized expertise in science. Initially, Furuichi demonstrated limited consideration for TTC. The researcher therefore proposed specific methods for transforming the TTC items "Ability to differentiate a scientific proposition from a non-scientific one" and "Ability to differentiate a scientific discourse from a dogmatic one." As a result, the TTC scores in CA improved, and Furuichi evaluated that the researcher's suggestions contributed to changes in GPC.

Wada's specialty is physical education. In Japanese elementary schools, teachers who are not specialists in science often teach science as well. Through lesson study, Wada's TSC improved in CA, and this was attributed to the researcher's suggestions regarding the GPC item "In particular, sequences to learn scientific concepts, and/or scientific processes (laboratories)."

Table 4. GPC Profiles of the Three Additional Teachers.

	Furuichi			Wada			Miyauchi		
	TTC	TSC	TCC	TTC	TSC	TCC	TTC	TSC	TCC
GPC for Questionnaire Survey	5.7	6.8	6.9	5.5	5.2	5.6	6.4	6.1	6.4
GPC for Lesson Study	13	12	14	16	18	8	14	22	27
Framework Conditions	0	0	0	0	0	0	0	0	0
Normative Concepts	1	0	1	1	1	0	0	0	2
Learn	0	3	2	1	4	2	0	4	1
Level of Development	0	0	0	0	0	0	0	1	0
Content Structuring	2	2	0	2	3	2	6	0	0
Interaction Control	0	0	1	0	0	0	0	0	0
Class Management	0	0	1	0	0	1	0	0	2
Action Plan	0	0	0	0	0	0	0	0	0
Execution Control	0	2	2	0	0	0	1	5	7
Lessons	5	3	3	8	8	2	1	4	8
Diagnosis	5	2	4	3	2	1	4	7	6
Understand	0	0	0	1	0	0	2	1	1

Miyauchi's specialty is Japanese language. In the district research group's lesson study, the high frequency of TSC observed in his CA was attributed to specific recommendations from the researcher concerning the GPC item "Competence to define the didactical contract and the situation to the learners, and to present them to learners as a space of active autonomy for them."

This study has several limitations. First, the primary analysis was conducted with a single science teacher, and the subsequent verification involved only three additional teachers. As a result, the findings should be interpreted with caution, as the sample size and diversity constrain the generalizability of the results. Moreover, all participating teachers had substantial teaching experience, which may have influenced how they interpreted and acted upon their CM. Therefore, future research should examine teachers with different backgrounds, including novice teachers, to further validate and extend the present findings.

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Exploring Physics Teachers' Use Of Lab Through Actor-Network Theory

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The study explored the application of Actor-Network Theory (ANT) in understanding physics experiment lessons, focusing on the development and implementation of the simplified Michelson Interferometer (MI). Traditional approaches to physics experiments often view tools as passive and prioritize human-centered teaching methods. ANT, however, highlights the active role of non-human actors in shaping networks of interactions. The research investigated two aspects of ANT application to teachers' use of laboratory activity: (a) the process of developing the interferometer and its associated actor networks and (b) teachers' use of new experimental tool and the networks formed during this process. Participants included physics teachers from two groups of teacher learning communities (total 32) and two experienced physics teacher for focus of observations and interviews. Data were collected through observations, surveys, and interviews and analytic framework was based on ANT. Findings revealed that developing the interferometer involved diverse human and non-human actors, creating a dynamic network. In the classroom, the experimental tool demonstrated agency by connecting teachers, students, and other resources, fostering meaningful interactions and emotional engagement. Teachers adapted and reinterpreted the experimental tool based on their goals and contexts, while students engaged with it to achieve experimental objectives, often generating unexpected results and insights. Ultimately, the study highlights the generative role of physics experiment tools in co-creating knowledge alongside students and teachers. Viewing such tools as active participants rather than passive objects offers an alternative perspective on teaching and learning physics, emphasizing the dynamic and collaborative nature of the process.

Keywords: Actor-Network Theory, experimentation, physics

Introduction

Laboratory has been the signature pedagogy in physics education and science education in general. The laboratory serves as more than a supplementary space; it is the signature environment for inquiry and the most distinctive method of both teaching and learning. At its core, physics is an experimental science. While mathematics provides the language, the laboratory experiment remains the most distinctive method of inquiry in science and science education. It is the space where abstract ideas meet reality. As a key pedagogical tool, the laboratory has evolved from the notion of scientific method as static steps to be taken into a dynamic process of observation, measurement, and revision practiced in groups (Hofstein and Lunetta, 2004; National Research Council [NRC], 2012).

The basic premise of using a laboratory as a pedagogical tool in school science education is that meaningful learning occurs when students have opportunities to manipulate equipment and materials to construct their own knowledge. Laboratory experience is essential for helping students move beyond rote memorization toward a deep, conceptual understanding of the physical world. Without the "minds-on, hands-on" interaction with physical phenomena, a student's understanding of concepts such as torque, electromagnetism, or entropy might remain purely symbolic and detached from the material world.

Beyond its pedagogical value, the laboratory serves as a benchmark for science pedagogy because science is fundamentally rooted in the interaction between theory and empirical evidence.

Science—and physics in particular—is defined by empirical **arguments**. Because the goal of scientific knowledge is to understand how things work, human-created explanations must be based on and supported by empirical evidence. Thus, science education aims to help students understand the ways scientists build explanations based on empirical evidence through direct investigative experiences (Berland & Hammer, 2012; Driver et al., 2000; NRC, 2012; Windschitl et al., 2008). The presence and quality of laboratory work act as a standard of authentic instruction; if the lab is missing or reduced to simple cookbook verification, the pedagogy is no longer truly scientific in the professional sense of the word (Lee & Butler, 2003).

The COVID-19 pandemic exposed a significant vulnerability in science education. During this period, students faced a profound lack of opportunity for hands-on physics laboratory experiences, which are traditionally the cornerstone of the discipline. This disruption turned physics into a purely theoretical pursuit for many, stripping away the essential minds-on, hands-on interaction required for meaningful learning. This crisis served as a catalyst for science teachers to be creative in filling the gap (Kang & Seo, 2021). Some teachers in South Korea developed simple and productive physics experimental devices designed for the home environment. The goal was to provide students with opportunities to easily manipulate on their own at home. By shifting the site of inquiry from the school lab to the student's home, experimental physics has been redefined as a flexible, decentralized practice, proving that high-quality inquiry does not always require industrial-grade equipment.

Whereas home-based experiments for classical mechanics are relatively accessible, a significant pedagogical gap persists regarding practical experiments for modern physics concepts. Current physics education lacks accessible, hands-on experimental devices that allow students to manipulate the abstract concepts of modern physics outside of a specialized laboratory. While students can easily drop a ball to study gravity at home, concepts like quantum spin, wave-particle duality, or atomic transitions are often relegated to abstract math or computer animations.

This research is motivated by the need to expand the home-lab revolution into the modern physics realm. By focusing on the development of simple and productive physics experimental devices specifically designed to teach modern physics concepts, we aim to provide students with the same empirical grounding in 20th-century physics that they currently enjoy in classical mechanics. This approach ensures that even the most abstract concepts in the curriculum are supported by a tangible, experimental foundation.

The purpose of this study is to understand how a newly developed simple laboratory setup is adopted by teachers. In particular, this study seeks to move beyond traditional human-centric analyses of education by exploring physics laboratory instruction through the lens of Actor-Network Theory (ANT). By adopting this symmetrical approach, the study aims to reveal the often-invisible influence of non-human actors—such as lab equipment, digital interfaces, and curriculum—on instructional designs of teachers. Ultimately, the study investigates the laboratory instruction as a complex network of interrelated entities, identifying which specific actors serve to catalyze or constrain productive instructional flows.

Theoretical Framework

This research is grounded in the emphasis on the role of experiments within the context of so-called the practice turn in the philosophy of science that refers to a broad shift away from analysing science primarily as a system of theories, propositions, and logical relations, and toward understanding science as a set of situated practices: what scientists *actually do* in laboratories, field sites, and research communities (Gooding, 2012; Schatzki et al., 2001).

Hacking famously argued in *his book (1983)*, "Experimentation has a life of its own" (p. 150), meaning that experiments can lead to discoveries even without a guiding theory. This claim has been supported by several historical reconstructions of detailed experimentation. In an analysis of three episodes in the history of modern science, Galison (1987) demonstrates that experimental traditions have their own continuity and logic that is distinct from the rise and fall of theoretical paradigms. Drawing on his background as an experimental physicist, Franklin (1989) reconstructs detailed experimental sequences from twentieth-century physics—including both successful discoveries and notable non-discoveries—to show how experimental knowledge is generated, stabilized, and sometimes revised. His inclusion of failed or inconclusive experiments is especially significant, as it highlights the contingent, iterative nature of experimental work.

Given the perspective that experiments are not merely servants of theory but are independent, practice-based sources of scientific knowledge experimental practice is seen as an epistemic activity. Experiments are structured sequences involving instrumentation, calibration, and error control that can produce reliable knowledge. This process is shaped by material, instrumental, and procedural constraints. Thus, experiments are open-ended, performative process (Pickering, 1993). Conducting experiments is not only about justification, but also about coping, adjustment, and emergence. Using Galison's historical account of particle physics experimentations in the 1950s and 1960s, Pickering demonstrates that scientific activity unfolds through a continuous struggle between human intentions and material resistance, which Pickering calls the mangling process (1993).

Scientists' struggles during experimentation are best understood through the interplay between human and material agency—the core premise of Actor-Network Theory (ANT) (Pickering, 1993). By rejecting a human-centred perspective, ANT highlights how human and non-human elements interweave to produce collaborative outcomes (Fenwick & Edwards, 2010; Latour, 2007; Law, 2009). As a post humanist framework, ANT is particularly effective for analysing scientific work, where the constant interaction between researchers, instruments, and experimental materials is foundational to constructing knowledge (Latour & Woolgar, 1986).

In his account of how human and material agencies interact, Pickering (1993) utilize the history of the bubble chamber—an instrument that uses superheated transparent liquid to detect electrically charged particles. Invented by Donald Glaser, who received the 1960 Nobel Prize for this achievement, the bubble chamber serves as a prime example of what Pickering called the mangle of practice - a dialectic between material and human agencies. Pickering demonstrates that repeated failures to meet experimental goals, such as increasing detection rates, forced an iterative process of modifying both the equipment and the goals themselves. These failures represent material agency or resistance. Because this resistance is unpredictable, material agency is emergent, requiring the human actor to respond and adapt in real time. Consequently, both human and material agencies are seen as temporally emergent—evolving together through the experimental process.

From the ANT perspective, learning is an effect generated by an assemblage of diverse elements. For example, a physics lesson can be viewed as an "assemblage" where the teacher (human), the student (human), and the lab apparatus (non-human) interact. The knowledge produced is an emergent property of this specific network. We draw on the idea that non-human elements, such as lab apparatus and digital tools are not passive tools but are actants that shape what can be learned. In this framework, the laboratory is viewed as a site of productive intervention. When a student manipulates a device, they are not just verifying an idea; they are engaging in a material practice that has its own internal logic. By analysing how the experimental device (non-human)

and the teacher and students (human) come together, we can understand how abstract concepts become tangible and real.

Methods

The authors devised a low-cost, student-operable Michelson interferometer intended for qualitative use in high school physics classrooms. To address the limitations of commercial interferometers—namely, high cost, complex alignment, and the need for precise optical components—the authors redesigned the apparatus using every day, easily obtainable materials, including convex mirrors commonly used as automobile auxiliary mirrors, slide glass as a beam splitter, and a low-power laser pointer. A key design choice was the replacement of plane mirrors and lenses with convex mirrors, which naturally expand the laser beam into a spherical wave. This eliminates the need for additional optical components such as lenses while making optical-axis alignment significantly easier for students. The expanded beam allows interference fringes to be projected directly onto a wall or sheet of paper, further simplifying the setup and reducing cost and fragility. Details of the lab setup is reported elsewhere (Kim & Kang, 2023). We introduced the interferometer to teachers in a local physics teacher workshop and examined how it was adopted—or not adopted—in their physics classrooms.

As an analytic framework we utilized the concept of translation in ANT to map the sociotechnical evolution of the physics experiment. Callon (1984) adopt the concept of translation to explain how scientific knowledge and social order are co-produced through networks of human and nonhuman actors. Translation is defined as the process through which actors construct, negotiate, and stabilize networks by defining roles, aligning interests, and enrolling both human and nonhuman entities so that collective action becomes possible. In a case study of marine science research, Callon identified four elements of translation: problematization, Interessement, enrolment, and mobilization. Problematization refers to the moment when the focal actor defines a problem and frames other actors' identities and roles in resolving the problem. Interessement refers to the efforts to lock actors into the roles defined in the problematization by using strategies, devices, or arguments that align their interests.

Enrolment refers to the successful acceptance and coordination of the proposed roles by actors, resulting in stabilized relationships within the network. Mobilization refers to the process by which a few actors come to represent and speak for many, ensuring that enrolled actors continue to act as expected. Mobilization is the final stage of the translation process. In this study, mobilization happens when the lab setup reaches a steady state when the students stop asking "What do I do next?" and start acting according to the roles the teacher assigned them. At the same time, the equipment stops being a collection of parts and starts being a measurement or observation system that is mobilized to represent physical reality, such as interference patterns.

Data were collected from multiple sources to examine how the interferometer was taken up in teachers' instructional practice. First, surveys were administered to workshop participants to document teachers' initial responses, perceptions, and intentions regarding the use of the interferometer. Second, in-depth interviews were conducted with two focal teachers to explore their decision-making processes, instructional adaptations, and experiences with adopting—or choosing not to adopt—the interferometer in their classrooms. Third, classroom observations of physics lessons were carried out to capture how the interferometer was enacted in practice, including patterns of teacher guidance, student engagement, and classroom interactions. Finally, instructional materials such as textbooks, handouts, and laboratory materials were collected and analysed to examine how the interferometer was integrated into existing curricular resources and instructional sequences.

Analysis begins by identifying how teachers translate the simplified interferometer into their lessons by mobilizing specific human and non-human actors. We track the four elements of translation to see how a stable network is formed. The analysis culminates in exploring the state of black-boxing, identifying the point at which the complex interrelations of the lab setup become a singular, unquestioned unit of experiment.

Results

Cases Of Non-Adoption

In this section, two cases of non-adoption of the experiment are described. As shown in the case descriptions, the teachers' goals for the experiments in both cases were inconsistent with the goals of the original design, which produced resistance in the experimental setup. This resistance was not accommodated by the teachers and therefore prevented the experiment from being adopted for classroom instruction.

Teacher H, a veteran physics teacher with 22 years of teaching experience, places a high value on meaningful laboratory experiences in physics learning. Despite this strong commitment to experimental instruction, Teacher H ultimately did not adopt the interferometer activity in the classroom.

During the workshop, Teacher H initially failed to produce expected interference patterns and spent relatively more time than other teachers to obtain predicted patterns. Although he succeeded in the end, Teacher H decided not to use the lab in his class. As the primary barrier, he indicated a concern about the reliability and interpretability of the experimental results, particularly the appearance of interference patterns that were perceived as ambiguous or unstable.

Teacher H also expressed reservations about the level of manual dexterity required to manipulate the apparatus, noting that fine adjustments might be challenging for students. This concern reflected an expectation for quantitative analysis of interference patterns—an outcome that the original lab design did not intend, but that Teacher H aimed for. In addition, the use of convex mirrors introduced visual noise in the interference patterns, which Teacher H felt could distract students or undermine confidence in the validity of the results.

Together, Teacher H concluded that the effort required of him and his students was not worth the results they could obtain from the experiment. Consequently, these concerns led Teacher H to judge that the activity did not sufficiently meet classroom expectations for clarity and robustness, resulting in a case of non-adoption.

Teacher Y, who has seven years of experience teaching general science, values experiments that are engaging, accessible, and easy for students to carry out when learning physics. Despite this emphasis on enjoyable hands-on activities, Teacher Y ultimately chose not to adopt the interferometer in classroom instruction. During the workshop, Teacher Y easily produced expected interference patterns and spent much time in explaining the patterns.

A primary barrier for his adoption was uncertainty regarding the experimental results, particularly concerns that the interference patterns might not be sufficiently stable or interpretable for instructional purposes. Similar to Teacher H, Teacher Y also noted limitations in supporting quantitative validation, which reduced confidence in using the activity to substantiate physics concepts rigorously. In addition, the visual noise introduced by the use of convex mirrors was perceived as potentially confusing for students. Collectively, these concerns led Teacher Y to conclude that the activity did not adequately align with instructional goals, resulting in a case of non-adoption.

A Case Of Adoption

In this section, one case of adoption of the experiment is described. Because the teacher applied the experiment in his teaching, the analysis focuses on how the experiment was utilized in the classroom, i.e., the translation process, resulting in the formation of an actor–network.

Teacher J, a physics teacher with six years of teaching experience and an alternative certification background in physics, brought prior experience with a failed Michelson interferometer experiment to the workshop. This experience shaped a strong instructional focus on laboratory activities that are both meaningful and reliably successful for students. As a result, Teacher J approached the interferometer with heightened sensitivity to issues of experimental robustness and classroom feasibility, prioritizing activities that could consistently produce interpretable results within typical instructional constraints.

Problematization

Teacher J framed the instructional problem in terms of both curricular alignment and classroom feasibility. As he explained, “Mere observation of interference patterns is not enough for the time and effort involved… I am trying to connect this to the wave interference conditions in the curriculum, such as path difference and interference conditions. Another concern is helping all students reliably produce stable interference patterns” (workshop interview). Through this framing, Teacher Y positioned successful and reproducible interference patterns as essential to the experiment’s instructional value, defining both conceptual coherence and experimental reliability as necessary conditions for adoption.

Mobilization

Teacher J designed and enacted the lesson by mobilizing a network of key human and nonhuman actors around the goal of understanding and quantifying interference. The instructional sequence began with lectures on the principles of superposition and wave interference, with particular emphasis on interference arising from path differences in the double-slit experiment. These conceptual resources were then extended through a dedicated lecture on the Michelson interferometer, which positioned the apparatus as a legitimate and meaningful tool for exploring interference phenomena.

Building on this conceptual foundation, Teacher J organized student-led experimental exploration using the simplified convex-mirror interferometer, incorporating performance evaluation to encourage active engagement and accountability. Through this sequence, students, curricular concepts, experimental apparatus, and assessment practices were aligned to sustain the instructional network, allowing the interferometer to function as a central actor in classroom practice.

In the process of Teacher J’s translation and actor–network formation, non-human actors—such as simulations, a thermal expansion apparatus, and a micrometre—exercised agency by affording, allowing, encouraging, suggesting, influencing, and rendering particular actions and understandings possible. In addition to the original lab setup, Teacher J created a digital video demonstrating how to set up the experiment so that students could watch it repeatedly as needed, and he added a thermal expansion bar for fine-tuning and a micrometre for measuring interference patterns.

As part of the translation process, the teacher problematized producing quantifiable results and additional laboratory materials were incorporated into the actor–network. In particular, a copper rod was introduced to enable fine-tuning of the interferometer through controlled thermal expansion. This material actor played a key role in stabilizing interference patterns and supporting

quantitative exploration, thereby strengthening the functional alignment of the network and reinforcing the instructional goal of understanding and quantifying interference.

At this point, the translation process is completed, and the actor–network becomes capable of producing instructional outcomes. Diverse actors—including the teacher, students, curricular concepts, experimental apparatus, and assessment practices—are successfully linked and coordinated to form a stable and functional actor–network. Through this alignment, each actor is effectively enrolled to contribute to a shared instructional goal, enabling the experiment to operate as intended within classroom practice.

Student reflections indicated that the experiment supported conceptual understanding of interference by making abstract wave concepts more tangible. As one student noted, "This experiment allows us to understand how the path difference changes as the laser displacement in the Michelson experiment is finely adjusted, resulting in different interference patterns. It provides a valuable introduction to the various properties of waves, which might otherwise remain abstract." This response suggests that the experimental activity helped students connect physical manipulation of the apparatus with underlying theoretical concepts, reinforcing the coherence of the actor–network in supporting learning outcomes as Teach J intended.

Discussion

This study examined how physics teachers adopt—or choose not to adopt—a newly designed laboratory device through the lens of Actor–Network Theory (ANT). The findings highlight the importance of conceptualizing physics laboratory instruction as a socio-material network rather than as a series of isolated instructional events. When the laboratory device became black-boxed, functioning as a stable and reliable agent within the network, it could be mobilized to support extended learning objectives beyond initial demonstration. Across cases, the teacher's emotional openness to uncertainty and adaptability in responding to resistance played a crucial role in the translation process, shaping whether the actor–network stabilized or unravelled.

This perspective encourages a shift away from teacher-centred explanations that attribute ineffective experiments to individual shortcomings and instead directs attention to the broader network of human and non-human actors that shape classroom dynamics. From this viewpoint, teacher professional development should be reconceptualized to address the multilayered actor–networks surrounding experimental tools, while the design of laboratory devices should intentionally support connections to existing curricular, material, and pedagogical networks. Such an approach foregrounds relational alignment over individual blame and highlights the distributed nature of instructional success.

Future research should investigate methods to foster diverse and creative translation processes when teachers engage with new pedagogical materials or instructional tools. In particular, studies are needed to examine how teachers adapt, reconfigure, or extend innovations as they interact with local classroom conditions and existing actor–networks. Furthermore, additional research should investigate how teachers' professional competence, encompassing their knowledge, attitudes, and values, interacts with non-human actors, such as instructional tools, representations, and materials, in the design of innovative lessons. Such work would deepen understanding of how pedagogical innovation emerges through socio-material interactions rather than through the transmission of fixed instructional models.

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Addressing Misconceptions Through Questioning: The Application Of Teacher Knowledge In A Primary Science Lesson

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This study explores the role of the knowledge deployed by an expert primary teacher during a lesson on the organs of the human body. The research attempts to uncover which elements of subject knowledge and pedagogical content knowledge underpin her classroom practice and how they interrelate. Employing an intrinsic case study design with a qualitative focus, the study analyses teaching episodes from video-recordings of four lessons with pupils aged 7 to 8 years. From the analysis of the knowledge revealed in her practice, three elements stand out: her knowledge of students' common misconceptions about the topic, her knowledge of questioning as a teaching strategy and her knowledge of facts. The teacher uses purposefully generated questions to elicit the pupils' knowledge about the position of the lungs, and the relationship between the size of the lungs and the heart. Through this approach, the teacher uncovers misconceptions about the topic, such as the idea that there are not two lungs and uncertainty about the heart's location. The findings highlight how the teacher's knowledge of common misconceptions shapes her questioning, enabling her not only to identify these misconceptions but also to promote pupils' knowledge construction by guiding them in re-evaluating their ideas. Furthermore, her science subject matter expertise allows her to identify and address the misconceptions effectively. The study underscores the interplay between subject matter knowledge and pedagogical content knowledge, demonstrating how these knowledge bases underlie the primary teacher's instructional practices.

Keywords: Primary science instruction; Teaching intervention; Case studies

Introduction

It is widely assumed that teachers' knowledge indicates instructional quality (e.g. Barendsen & Henze, 2017) and that teaching requires subject matter knowledge (SMK) and pedagogical content knowledge (PCK) (Shulman, 1986). Science teachers' PCK has been studied extensively, with various conceptualisations (e.g., Gess-Newsome, 2015; Park & Oliver, 2008), often considering SMK as a prerequisite. Moreover, studies on PCK have focused more on secondary than primary school teachers (Chan & Hume, 2019). This study examines the SMK and PCK of a primary teacher, focusing on interconnections between PCK elements and between PCK and SMK. These connections are of particular interest, as both the depth of the teacher's knowledge and its connection demonstrate the strength of her understanding and its transfer to the classroom (following Barendsen and Henze (2017), and Park & Chen (2012), referring to PCK). Previous studies highlight differences in how science teachers' knowledge impacts student performance, though combining SMK and PCK is crucial for addressing misconceptions (Sadler et al., 2013). Further research is needed on how high SMK and PCK teachers engage students (Chen et al., 2020) and how SMK influences PCK (Sen et al., 2018).

The topic of this study, human body, is complex. Research reveals that students aged 7 to 8 can locate two or more internal organs but often struggle to link them (Dempster & Stears, 2014). For students to develop their understanding of the organs, teachers must help students transition from

abstract ideas to detailed understanding, emphasising the characteristics and differences of each organ (Andersson et al., 2019). This requires teachers to be knowledgeable about how students learn, and to have a range of teaching strategies at their disposal.

The study was intended to address the following research question, what are the main elements of SMK and PCK that underpin a primary school teacher's practice in teaching the organs of the human body and how do they interrelate with each other? Our contribution to the research literature on science teacher knowledge is threefold: a) Studying an expert teacher, which is expected to provide access to high SMK and PCK; b) Integrating the study of SMK, less explored in science, with PCK, as well as their interconnections; c) Focusing on a primary school teacher, who has received less attention in studies on science teacher knowledge than secondary school teachers.

Methodology

This research was designed as a case study design (Yin, 2018). We selected an experienced teacher (26 years as primary teacher, with a degree in Primary Education and a doctoral thesis in science education) working in a state school in southern Portugal. Four consecutive lessons, each lasting approximately 1 hour, on the organs of the human body were videorecorded, over the course of a week with second-year pupils aged between 7 and 8.

The data collected was analysed with the PCK categorisation of Park & Oliver (2008), considering Knowledge of Instructional Strategies and Representations for teaching science (KISR), Knowledge of Students' Understanding in science (KSU) and Knowledge of the Science Curriculum (KSC). For categories pertaining to SMK, due to the absence of specific categorisations with respect to science teachers, we drew on the doctoral thesis of Luís (2021), focusing on (biological) subject matter knowledge, encompassing knowledge of: observation procedures and techniques; concepts and associated examples; laws, principles and theories; models associated with the content; and of biological facts and phenomena.

Results

In order to answer the research question, we present two situations in which we can see how the teacher uses different types of knowledge to support her students' learning about organs.

What stands out most is her knowledge of students' possible misconceptions about the organs of the human body (KSU). When approaching, the teacher mainly shows knowledge of questioning as a teaching strategy (KISR). Through questioning, the teacher encouraged her pupils to articulate their existing ideas and to reflect on these. An example occurs during an activity based on a worksheet depicting two bodies, male and female. The pupils call out various ideas about the organs of the body, including the four (heart, lungs, stomach and kidneys) targeted by the teacher. At this point she says:

> Teacher: *Can you all draw these organs here in the outline of the women – or the girl – and the man.* [Focusing the activity on eliciting prior knowledge about the location of the organs].

In doing so, she reveals her knowledge of possible student misconceptions regarding the position of the organs. She tries to elicit her pupils' intuitions through questions such as the following, in which she asks the pupils to say organs they feel most confident of locating:

> Teacher: *And you, Maria, which organ are you confident about? Where is it?* [...] *Are the lungs in the middle* [pointing]*?*

Two misconceptions arise during this episode. First, inaccurate information about the number of lungs:

> Teacher: *How many lungs are there?*
>
> [The teacher repeats various students' answers: two, one]
>
> Teacher: *Is it just one big lung at the front? But I'm talking about lungs* [stressing the plural 's']. *Is that because it's one big one? Is its name in the plural?*

The teacher is aware of the misconception that some students may have regarding the number of lungs, and for this reason draws out these ideas with her questions, and supplies the right answer, thus demonstrating her knowledge of the facts of the subject (there are two lungs) (SMK).

Second, there arises a misconception about the position of the organs, this time the heart. The teacher continues in the same way, using the questioning strategy, but this time she also uses questions to find out how the students perceive their hearts:

> Teacher: *You're saying you feel it here, like Mel?* [Touching her neck] [...] *I'm puzzled. So, the heart is on the left, Mel feels her heart in her neck. Can you feel your heart in your foot?* [...] *Where do you think we can feel our heart, in our knee? Or here?* [She touches her neck] O*r in our foot? Does it make a noise?*

Finally, we infer that the teacher has SMK regarding the slight displacement of the heart to the left, which allows her to be aware of misconceptions about the position of the heart. Likewise, she also knows the fact of the connection between the heart and the size of the left-hand lung. While questioning the pupils about this curious difference in size between the two lungs the following exchange occurs:

> Student: *Because one must have good oxygen, and the other mustn't have oxygen.*
>
> Teacher: *No, that's not why. Ah, look what's in the middle here, come on, what's in the middle?* [...] *That's the heart in the middle. So, to make room for the heart, the other organs have to fit in. And the heart is a little more to the left here, it's not quite in the middle, it's a little more to the left.*

While addressing these misconceptions, in the second situation she goes on to demonstrate awareness of similar misconceptions about whether these organs differ between men and women:

> Teacher: *The worksheet about the body that I gave you, there is a man and a woman on it. Are these organs the same in men and women?*

In response to various doubtful answers, the teacher draws one her knowledge that the lungs and heart are essentially the same in men and women, albeit noting the knowledge of the fact of the relativity of the size for everyone.

> Teacher: *Men and women have the same lungs and the same heart, but a very big person has a bigger heart.*

In summary, the teacher not only uses her KISR, with the use of questioning as the main strategy, to elicit misconceptions from the pupils (supported by KSU), but also uses the questions and answers that emerge during the exchanges to construct basic knowledge of the subject. Throughout the dialogical teaching process, the teacher gives evidence of SMK, namely about the facts underpinning the above-mentioned PCK and especially her knowledge of misconceptions.

Discussion

This study has shown how a primary education teacher's SMK and PCK interact at the point when she adopts a questioning strategy to address misconceptions about the organs and guide the pupils to construct their knowledge. We concur with Akman and Öztekin (2023) regarding the connection between in-depth SMK and knowledge of pupils' misconceptions. We have identified the questions used by the teacher to elicit the pupils' existing notions about the number and position of the lungs, and the position of the heart, along with the fact that these organs are identical in men and women. Her questions are staged so as to guide the pupils away from misconceptions towards the correct subject matter knowledge (Chin, 2007). The use of questioning not only enables misconceptions to be identified, but also facilitates the construction of knowledge, by making the pupils rethink their original ideas and reformulate them where necessary (Benedict-Chambers et al., 2021). The SMK that seems to underpin mainly her knowledge of misconceptions refers to factual knowledge. This may be conditioned by the content of the lessons observed and requires further study. We believe that this study can contribute to how an expert teacher's knowledge supports her approach to teaching particularly complex topics in relation to students' misconceptions.

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Section: Evaluating The Impact Of In-service Teacher Training

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Exploring The Impact Of A Multidisciplinary Sustainability Course For Teachers: Analysis Through GreenComp

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This paper presents the results of the second cycle of a training course on sustainability for in-service teachers, designed according to a Design-Based Research approach. The course was designed to be multidisciplinary, based on the European GreenComp framework. Analysis of the lesson plans developed by teachers and feedback questionnaires shows how the training supported the design of activities that integrate different dimensions of sustainability and are strongly anchored in everyday life contexts. The results also highlight the central role of collaborative work and co-design in supporting sustainability-oriented teaching practices.

Keywords: Sustainability, Teachers, Multidisciplinary

Introduction

Educating for sustainability means dealing with complex issues that not only concern the environment but also involve social, economic and cultural aspects (UNESCO, 2017). For this reason, teacher training cannot be limited to individual disciplines but must offer interdisciplinary and participatory workspaces where it is possible to reflect on teaching practices and design activities that help students develop critical thinking, awareness and the ability to act (Blonder et al., 2014; Fensham-Smith, 2019; Monroe et al., 2019).

The work presented in this contribution is part of a broader research project developed according to a Design-Based Research (DBR) approach (Guisasola et al., 2017). The project began with the design of a Teaching–Learning Sequence on the greenhouse effect, designed to address students' mental models and support teachers in introducing the physical principles underlying the phenomenon (Toffaletti et. al., 2022). However, it became clear that a perspective focused exclusively on physics was not sufficient to adequately address the issue of sustainability. Based on this awareness, a multidisciplinary training course on sustainability was designed for teachers in service, with the involvement of university professors from different departments.

This paper presents the results of the second cycle of the course, which was redesigned on the basis of previous experiences and gave greater space to collaborative work, interdisciplinary integration and shared planning.

Theoretical Framework

The theoretical framework that guided this research is GreenComp (Bianchi et al., 2022), the European framework for sustainability skills. It interprets sustainability as an integrated set of knowledge, skills and attitudes that guide the way people think, make decisions and act. The framework provides a structure that can be adapted to different educational contexts and used as a guide for instructional design.

The framework is organised into four interconnected areas of competence. The first concerns sustainability values and includes reflection on personal and collective values, attention to equity and intergenerational justice, and recognition of the value of nature. The second area focuses on understanding complexity through skills such as systemic thinking, critical thinking and the ability to define sustainability issues in relation to context. The third area is dedicated to the future perspective, promoting the imagination of sustainable scenarios and the ability to deal with

uncertainty and change. Finally, the fourth area concerns action for sustainability, including individual initiative, collective action and participation in decision-making processes.

Together, these four areas offer a coherent framework for supporting educational design that can integrate the value-based, cognitive and operational dimensions of sustainability, providing a useful method for analysing teaching practices and designing them.

Methods

The second cycle of the teacher training program was conceived and implemented within a DBR framework. The course was designed as an iterative intervention aimed at supporting teachers' professional development and informing the refinement of subsequent design cycles. The course took place over two intensive days. This decision was made based on the results obtained in the first cycle (Fiorello et al., 2024) with the aim of improving accessibility while preserving the multidisciplinary structure of the intervention.

On the first day of the course, the conceptual and methodological aspects of sustainability and sustainability education were presented, which then served as resources for the teachers' project work the following day. The day was divided into four thematic sessions. The course began with an introduction to the European framework of sustainability competences (GreenComp). This was followed by three sessions dedicated to environmental, social and economic sustainability. These sessions combined disciplinary perspectives with explicit attention to sustainability as a multidimensional construct, supporting participants in connecting scientific content with broader social, economic, and cultural dimensions. In these sessions, the aim was not only to provide disciplinary perspectives on the topic, but also to highlight how scientific content is linked to other aspects of sustainability. The structure and main topics of the first day are summarized in Table 1.

Table 1. Structure and main topics of the first day of the course.

Session	**Main contents**
Introduction to GreenComp	Presentation of the European framework for sustainability competences (GreenComp): its four competence areas. Discussion on how GreenComp can guide educational practices and lifelong learning for sustainability.
Environmental sustainability	Scientific context relating to climate change and decarbonisation. Analysis of climate data on a global and Alpine scale (temperature, precipitation, snow cover) and the physical basis of greenhouse gas effects. Discussion on energy production and consumption, renewable sources and decarbonisation.
Social sustainability	Reflections on the social and cultural dimensions of sustainability. Legal and anthropological perspectives on community-based governance and the concept of 'territories of life' in mountain areas. Exploration of human-environment relationships, rights and responsibilities, and the role of collective domains in ensuring dignity, justice and long-term coexistence.
Economic sustainability	Introduction to economic indicators for sustainability and the multidimensional nature of sustainable development. Analysis of the ecological footprint and Earth Overshoot Day. Discussion on consumption patterns, global inequality and strategies to reduce humanity's environmental impact.

The second day, on the other hand, was designed as a collaborative and project-based workshop. Participants worked in mixed groups (3 groups), composed in such a way as to ensure diversity in terms of disciplinary background and educational level. Teachers were asked to design educational activities inspired by the GreenComp framework using the Trialogical Learning Approach (CIT.).

Data collection was based on two main sources. At the end of the course, a satisfaction questionnaire was administered. The questionnaire was identical to the one used in the previous cycle, allowing for comparability between iterations, and was designed to gather teachers' perceptions of the organization, content and perceived relevance of the training program. The second resource for analysis concerns the lesson plans developed by the working groups. These constituted a central source of qualitative data, providing information on how teachers interpreted and implemented sustainability skills within their teaching projects.

The teaching plans were analysed qualitatively based on identifying how the different dimensions of sustainability – environmental, social and economic – were developed and integrated into the proposed activities. Attention was paid to the use of elements related to the GreenComp framework and the conceptual structures used by teachers to frame sustainability issues. The aim of this analysis was to evaluate the current intervention and refine the course design for future iterations. At the same time, the qualitative analysis of the feedback questionnaires aimed to capture the suggestions and critical reflections expressed by the teachers. Attention was paid to teachers' perceptions of collaborative work and co-design opportunities, as these were critical issues that emerged from the first training cycle and which we wanted to see improved in this cycle.

Results And Discussion

To give an overview of the teachers' proposals, Table 2 outlines the three lesson plans developed, highlighting the topics addressed, the activity structure, and the resulting artefacts.

Table 2. Summary of the lesson plans developed by participating teachers.

Lesson Plan	**Main contents and artefact**
Group 1: Food waste (lower/upper secondary)	Brainstorming on food waste; identification of local contexts to investigate (markets, restaurants, canteens, households); design of questionnaires and interviews; field data collection; selection and analysis of results; creation of a short documentary to communicate findings to the community. Artefact: documentary on food waste.
Group 2: Everyday energy saving (primary/lower secondary)	Analysis of students' everyday behaviours related to energy use; class discussion of possible improvements; collaborative construction of a "good practices" list to promote energy saving at school and at home; dissemination of the final document within the school community. Artefact: digital energy-saving decalogue.
Group 3: Fast fashion and textile supply chain (lower secondary)	Data collection on students' wardrobes (number of items, frequency of use); graphical representation of the data; reflection on environmental and social impacts of the textile industry; activities aimed at raising awareness of personal consumption habits; creation of a traffic-light tool to guide more responsible clothing purchases. Artefact: traffic-light decision tool.

Analysis of the teaching programmes developed by the teachers shows that each group interpreted the theoretical framework presented during the course (the multidimensional nature of sustainability and GreenComp skills) in a different way. In fact, the proposals vary in terms of pedagogical approaches and teaching choices.

The first project, focusing on food waste in the local area, is characterized by a strongly collective and community-oriented approach. The social dimension of sustainability is a key aspect of the planned activities. The project involves guiding students in exploring the phenomenon through research-based activities, including interviews and data collection. This approach helps students feel actively involved in the issue and develop a sense of shared responsibility towards something they perceive as real and close to their everyday lives. From GreenComp's perspective, the project activates skills mainly in Areas 1, 2 and 4. In Area 1, students develop an awareness of the value of food and its social role (1.1 Valuing sustainability) and reflect on issues of equity and justice in the distribution of resources (1.2 Supporting fairness) in Area 2, investigative activities promote systemic thinking (2.1), which is essential for understanding the relationships between food production, distribution, consumption and waste, and critical thinking (2.2), through the evaluation and reinterpretation of the information gathered in the documentary. Through brainstorming and peer discussion of research questions, it is possible to frame the problem (2.4). Finally, the production of the documentary constitutes a form of collective action (4.2) and an expression of political agency (4.1), as students communicate their findings to the wider community and position themselves as agents of change. Overall, the project coherently integrates the environmental, social, economic and cultural dimensions of sustainability through inquiry-based activities rooted in real-world contexts.

The second project focuses on energy saving in everyday behaviour and represents an intermediate approach between the first lesson plan, where activities are more focused on collective attitudes, and the third lesson plan, which is purely individual. In fact, teachers have designed activities that encourage students to reflect on their energy consumption habits and gradually develop a series of good practices to share with the school. From the point of view of the multidimensionality of sustainability, the project mainly addresses the environmental dimension, linked to the reduction of energy waste, but also involves the social dimension, as the final document seeks to influence shared practices and promote new behavioural norms. The greencomp competences activated are mainly related to Areas 1 and 4. In Area 1, the project supports the value of sustainability (1.1) by encouraging an understanding of energy as a shared and limited resource. Area 4 emerges in two aspects: students reflect on their personal responsibilities through individual initiatives (4.3) and the development of a collective "ten-point charter" promotes collective action (4.2) aimed at influencing the behaviour of the entire school community.

The third project, which addresses the issue of fast fashion and the textile supply chain, takes a more individual approach and is closely linked to the students' everyday experiences. The activity starts with an analysis of the students' personal wardrobes, how often they wear their clothes and why they buy them. This makes the topic concrete and relevant to their experience, helping them to reflect on their own consumption habits. From a sustainability perspective, the project addresses both environmental aspects, linked to the impact of the production chain, and social aspects, such as working conditions and workers' rights, inviting students to reflect explicitly on the ethics of consumption. The GreenComp skills activated in this project cover all four areas. In Area 1, reflection on personal consumption is linked to the importance of promoting sustainability (1.1) and focusing on fairness and rights within the production chain (1.2). Area 2 is activated through systemic thinking (2.1), necessary to grasp the complexity of the textile supply chain, critical thinking (2.3), necessary to analyse personal habits and assess their impact, and problem

definition (2.4), supported by meetings with experts and analyses conducted during the visit. Area 3 is involved through the invitation to plan future purchasing decisions (3.1), linking present actions to possible future scenarios. Finally, Area 4 is supported by the use of the decision-making "traffic light" system for individual use (4.3) and by opportunities to share results with the wider community (4.2).

The analysis of the questionnaires administered at the end of the course provides a very positive overall picture. Participants expressed a high level of satisfaction with both the organisation and the overall quality of the course. Almost all teachers perceived the programme as well-structured and carefully planned, with clear objectives and well-prepared materials. These results suggest that the more compact and practice-oriented format adopted in the second cycle was perceived as coherent and effective. The course content was also highly appreciated. All participants described the training as interesting and motivating, and around 70% said they had learned "many" new concepts. The trainers received very positive evaluations: most teachers found them clear and engaging, with no negative comments. Almost all participants acknowledged that the course content was directly applicable to their teaching practice, and all indicated that what they had learned could be used in their professional context. Furthermore, the fact that most teachers have already applied some ideas in their practice, or intend to do so shortly, clearly indicates the perceived relevance of the course. Another significant result concerns collaboration between teachers. While this emerged as a critical issue in the first cycle, the second cycle saw a marked improvement: around 85% of participants reported an increased ability to work in teams and collaborate with colleagues. The open responses highlighted above all the value of the second day, which was mainly devoted to workshops and shared design activities, where some participants suggested dedicating more time to design.

Conclusions

Analysis of the teaching plans and questionnaires from the second cycle indicates a development in the way teachers interpret and translate sustainability into teaching planning. The questionnaire data show a very positive overall assessment. Teachers particularly appreciated the opportunity to plan collaboratively, confirming co-design as a central and effective element of the programme.

The teaching plans reveal a tendency to frame sustainability through concrete issues closely related to students' everyday experiences, such as food waste, energy use and consumption practices. This suggests that sustainability is increasingly being addressed not only as a set of concepts to be taught, but as a dimension that is part of everyday life.

GreenComp has emerged as a reference point for educational design, providing a framework that has guided the integration of sustainability-related skills into the proposed activities. Overall, the results show a strengthening of sustainability-oriented educational planning, combining scientific content, participatory approaches and a focus on everyday practices.

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Enhancing Teachers' Beliefs, Self-Efficacy And Professional Knowledge Through In-Service Teacher Professional Development Programs On The Use Of (Interactive) Experimental Videos

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In the context of digital progress, the implementation of Information and Communication Technologies (ICT) in schools is becoming increasingly frequent. Innovative learning media, such as (interactive) experimental videos, are emerging as a significant component in physics education. These technologies are characterized by high interactivity, which facilitates a constructivist approach to domain-specific learning. Despite the increasing availability of such ICT for physics education, its utilization remains limited. This phenomenon can be attributed to a combination of factors, including teachers' beliefs, self-efficacy, technology commitment, and professional knowledge. Specifically, weak beliefs and a lack of professional knowledge regarding the integration of (interactive) experimental videos, coupled with the subjective perception of being unable to meet the digital requirements, can lead to reduced utilization in physics lessons. The implementation of professional development (PD) programs can be a key element in minimizing these effects. For example, the presented study shows that the integration of (interactive) experimental videos within a PD program has a positive effect on professional knowledge and ICT reaction beliefs.

Keywords: beliefs, in-service teacher programs, (interactive) experimental videos

Introduction

Information and communication technology (ICT) is becoming an increasingly relevant part of teaching practice (KMK, 2016). In classrooms, ICT offers innovative approaches to foster students' learning. However, it also creates new demands on teachers' professional development (Caena & Redecker, 2019). Teachers need digitalization-related skills to effectively integrate ICT in their teaching practice (Fernández-Batanero et al., 2020). This is particularly important for domain-specific ICT, since its meaningful implementation depends on the connection between general digitalization-related skills and domain-specific didactic knowledge, as highlighted in current frameworks (DigCompEdu; Redecker, 2017).

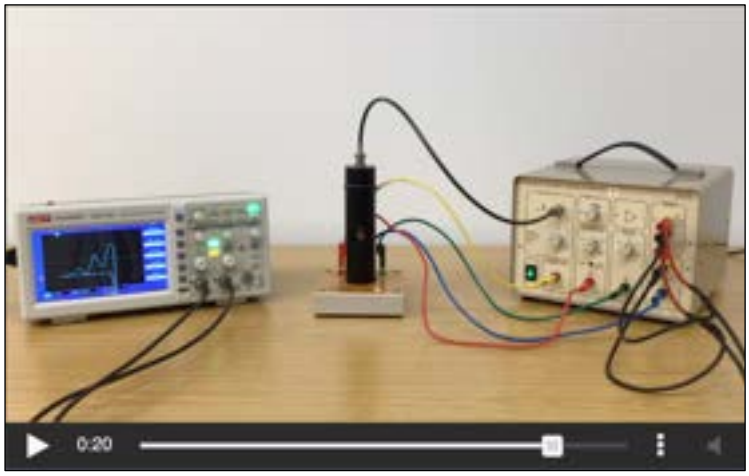
Although the frequency of ICT utilization has increased in recent years (Drossel et al., 2024), this mainly relates to established and cross-disciplinary ICT. More innovative and domain-specific ICT, such as (interactive) experimental videos, is still rarely used in classrooms (Drossel et al., 2024; Vogelsang et al., 2019). This can be attributed to teachers' ICT beliefs, their self-efficacy as well as their professional knowledge. Rudimentary digitalization-related skills (Huber et al., 2020) and weak beliefs coupled with the perceived inability to meet digital demands can lead to low utilization of ICT in classrooms.

Despite the availability of in-service teacher professional development (PD) programs, teachers only participate to a limited extent, partly due to a lack of adequate and contextually appropriate offerings (Eickelmann, 2019). Therefore, further tailored domain-specific PD programs are necessary to promote teachers' beliefs, their self-efficacy and their professional knowledge regarding the implementation of domain-specific ICT in lessons (Eickelmann, 2019).

Theoretical Background

(Interactive) Experimental Videos

Figure 1. Experimental Video of the 'Franck-Hertz experiment'. The students' task is to observe the typical curve displayed on the oscilloscope.



One such example is the presented PD on (interactive) experimental videos. Experimental videos are defined as the combination of the classic demonstration experiment and the digital tool of videography (Stinken-Rösner & Meier, 2023). So, initially, these are videotaped demonstration experiments, showing the individual steps of the experiment in linear sequence (see Figure 1). While watching the video, the students observe the outcome of the experiment and may record measurements. In this case, students act as 'passive' viewers in an observing role (ICAP-model; Chi & Wylie, 2014), as is also the case when a demonstration experiment is carried out in reality. To increase cognitive activation, interactive H5P elements can be integrated into experimental videos. These videos, then referred to as interactive experimental videos, are characterised by the fact that students can actively interact with the medium, thereby achieving a deeper understanding of the domain-specific content (Meier et al., 2022a).

In the literature on domain-specific education, (interactive) experimental videos are particularly present in practice-oriented articles (e.g. Meier et al., 2022a; Pfafferodt et al., 2023), highlighting their potential for inclusive teaching and learning (Stinken-Rösner et al., 2023). However, empirical studies dealing with the implementation of experimental videos in physics lessons, as well as teachers' attitudes towards the use of experimental videos, are still rare. A first survey revealed that science teachers generally have a positive attitude towards (interactive) experimental videos (Meier et al., 2022b). At the same time, it became clear that a group of sceptics attributed greater importance to real-world experiments. They worry that interactive experimental videos could replace real-world experiences in physics lessons (Meier et al., 2022b). This concern can be explained by the fact that these teachers do not regard the (interactive) experimental videos as a supplement to real-world experiments, but as a substitute with no added functional value for the experimental process (SAMR-model according to Puentedura, 2006).

Professional Knowledge

Successful integration of ICT into teaching practice largely depends on teachers possessing ICT-related professional knowledge. The TPACK framework proposed by Mishra and Koehler (2006) combines three main components of teachers' knowledge: pedagogical, content and technological knowledge. Pedagogical knowledge (PK) encompasses knowledge of teaching methods and learning strategies. Content knowledge (CK) refers to domain-specific knowledge about the

content to be taught in lessons. Finally, technological knowledge (TK) describes the use of digital tools and software like tablets and presentation programs.

These dimensions are not considered separately but form four important intersections (Mishra & Koehler, 2006). Pedagogical content knowledge (PCK) is equivalent to domain-specific didactic knowledge and focuses on how a particular domain-specific content can be taught effectively. Technological pedagogical knowledge (TPK) deals with how ICT can be used in a didactically meaningful way in the classroom. Technological Content Knowledge (TCK) describes how ICT can be used in the subject. Finally, the central component is Technological Pedagogical Content Knowledge (TPACK). It describes the knowledge required to convey domain-specific content in a meaningful way using ICT in the classroom.

Current research on professional knowledge suggests that targeted interventions can effectively promote STEM teachers' TPACK. Specialized courses within teacher education have resulted in significant improvements in pre-service STEM teachers' TPACK (e.g. Stinken-Rösner et al., 2023; Chai et al., 2010). Furthermore, it has been found that specific in-service teacher PD programs can also contribute to an increase in their TPACK (Lehiste, 2015).

Teachers' ICT Beliefs

In order to implement ICT in a pedagogically meaningful way, teachers need to purposefully apply their professional knowledge in the classroom. (Stinken-Rösner et al., 2023). However, the actual utilization of ICT in teaching practice is not only a matter of teachers' professionalization but also closely related to their subjective beliefs. Schmidt and Reintjes (2020) investigated the ICT beliefs of pre-service teachers and identified three central forms. First, so called reaction beliefs that conceptualize ICT primarily as an instrumental tool to support existing teaching practices. Second, design beliefs that emphasize the pedagogically meaningful integration of ICT in classrooms. Third, identity beliefs that relate to teachers' self-concept in the context of digitalized teaching.

Self-Efficacy

Self-efficacy in general 'refers to beliefs in one's capabilities to organize and execute the courses of action required to produce given attainments' (Bandura, 1997, p. 3). A domain-specific form of this construct is described by the computer-related self-efficacy, which refers to one's confidence in one's ability to successfully perform computer-related tasks (Spannagel & Bescherer, 2009). In the context of utilization of ICT in lessons, computer-related self-efficacy is of central importance as it substantially determines whether certain behaviours (such as integration of ICT in the classroom) are initiated at all (Bandura, 1977). Teachers with a high level of self-efficacy exhibit strong confidence in their ability to use ICT in teaching and are more persistent when encountering problems. Consequently, self-efficacy is a key predictor of successful ICT implementation in teaching practice.

A recent meta-analysis examining the effects of PD programmes on teachers' self-efficacy revealed statistically significant medium effect sizes (Zhou et al., 2023). These findings were confirmed by further studies (e.g. Yang, 2020).

Technology Commitment

Technology commitment consists of three components: Technology acceptance, technology competence beliefs and technology control beliefs. According to Neyer et al. (2012) technology acceptance refers to the subjective assessment of technical advances. Technology competence beliefs describe the subjective evaluation of one's own competencies in utilizing established ICT

and adapting innovative ICT for teaching practice. Technology control beliefs are defined as the degree to which a person perceives having influence or control over technological processes.

Studies on technology acceptance indicate that ICT-related beliefs influence one's intention to use ICT, which in turn is considered a central predictor for actual ICT utilization (Venkatesh et al., 2003). Therefore, PD programs are required to systematically foster teachers' digitalization-related skills and, consequently, strengthen their technology commitment. Current studies on pre-service teachers indicate a higher level of success in the use of ICT when technology acceptance is strongly developed (Köstler & Wolff, 2025). These findings suggest that, for in-service teachers, higher technology acceptance may result in increased implementation of ICT in physics lessons.

PD Program Concept

As explained above, teachers' beliefs and their high level of professional knowledge are considered essential prerequisites for the successful use of ICT in the classroom. However, these characteristics do not develop automatically but require targeted support. In-service teacher PD programs could play a key role here, as they offer structured learning opportunities. Against this background, the concept of the designed pd program (see also Ziegler and Stinken-Rösner, 2024) is presented below (Table 1).

Table 1. Description of the designed PD program.

Module 1 (7 hours)	
Actions	Aims
At the beginning, the participating teachers are introduced to the use of videos in physics lessons, along with a definition of experimental videos. This is followed by an input on design principles for demonstration experiments and multimedia applications, as well as on different scenarios for using experimental videos in teaching practice. Subsequently, the participating teachers independently produce experimental videos based on the introduced design principles. For this purpose, they use prepared experiments or alternatively experiments of their own choice. The produced experimental videos are then exchanged with the task of adding a voice-over that describes the experimental procedures (video dubbing). Finally, the participating teachers receive peer feedback from other participants for their experimental videos.	The participating teachers should be able to… … distinguish between different types of videos. … identify design principles in experimental videos. … independently produce an experimental video of a demonstration experiment, considering design principles for demonstration experiments. … add a voice-over to an experimental video.
Module 2 (4 hours)	
The pedagogical usefulness of interactive elements in digital media is discussed, with reference to the ICAP model as a theoretical framework. This is followed by an introduction to the 'Lumi' software and, more specifically, the various interactive H5P tools it provides. Subsequently, the participating teachers integrate the interactive H5P tools into their experimental videos produced in the first module. Finally, teachers receive peer feedback on their interactive experimental videos from other participants.	The participating teachers should be able to… … describe the pedagogical usefulness of interactive elements in digital media in physics lessons. … produce interactive experimental videos.
Module 3 (4 hours)	
Participating teachers visit the student lab with a class from their school. There, the students work with experimental videos either as an independent learning medium or in combination with a real-world experiment. The experimental videos used for this purpose are produced in advance by academic staff. During the implementation in the student lab, the teachers observe the students' learning processes and interactions.	The participating teachers should be able to… …assess the pedagogical usefulness of (interactive) experimental videos across different scenarios.

Research Question

Previous research shows that the utilization of (interactive) experimental videos by teachers has not yet been sufficiently researched. An initial study shows that the majority of teachers have a positive attitude towards experimental videos, but there are also concerns about their use (Meier et al., 2022b). However, the extent to which in-service teacher PD programs affect teachers' professional knowledge, their beliefs towards, as well as the resulting implementation of (interactive) experimental videos in practice was not considered. Therefore, the present study investigates the following research question:

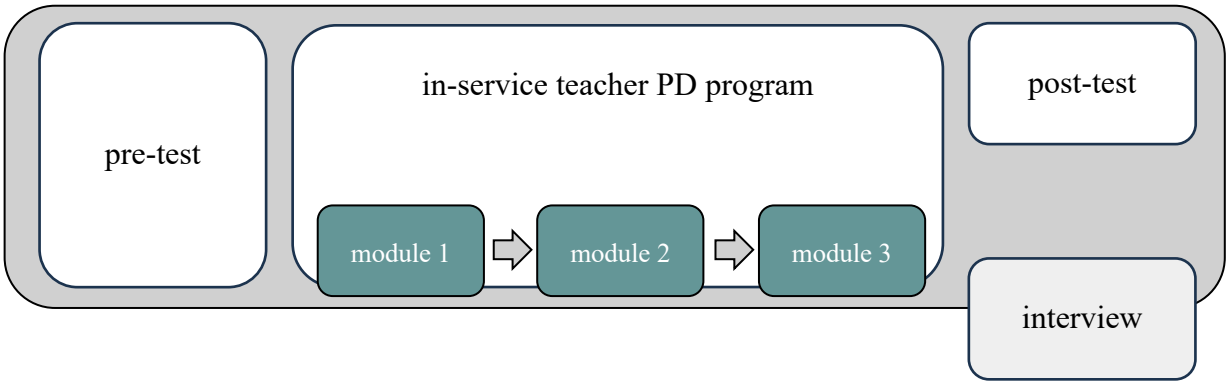
To what extent does participating in a PD program on the use of (interactive) experimental videos influence in-service physics teachers' technology commitment, their ICT beliefs, their self-efficacy and their professional knowledge regarding the use of ICT?

Methods

Study design

The data is collected using a mixed-methods approach (see Figure 2). In a pre-post design, the quantitative data were collected using a standardized questionnaire, which includes, among others, well-established scales on technology commitment (TC; Neyer et al., 2012), ICT reaction beliefs (ICT RB; Schmidt & Reintjes, 2020), self-efficacy (SE; Beierlein et al., 2012) and professional knowledge (Stinken-Rösner, 2021). All items are recorded on a six-point Likert scale (1 = strongly disagree, 6 = strongly agree). Regarding professional knowledge, a specific methodological consideration applies. As (interactive) experimental videos are not yet widely used in teaching practice, it can be assumed that the participating teachers had no prior experience with this medium. Consequently, the TK and TCK scales were operationalised with reference to digital media in general at the pre-test measurement and with reference to (interactive) experimental videos at the post-test measurement. As a result, changes over time cannot be directly assessed for these scales. However, there are comparisons between pre- and post-measurements possible. In addition, qualitative semi-structured group interviews were conducted with the participating teachers following the completion of the PD program to explore the conditions for success and the barriers to the implementation of ICT integration.

Figure 2. Visualization of the study design.



Sample

The PD program was offered three times. Three teachers took part in the first round, while five teachers each took part in the second and third rounds. In total, 12 physics teachers took part in the accompanying study (50 % male, 50 % female) and completed both pre- and post-test.

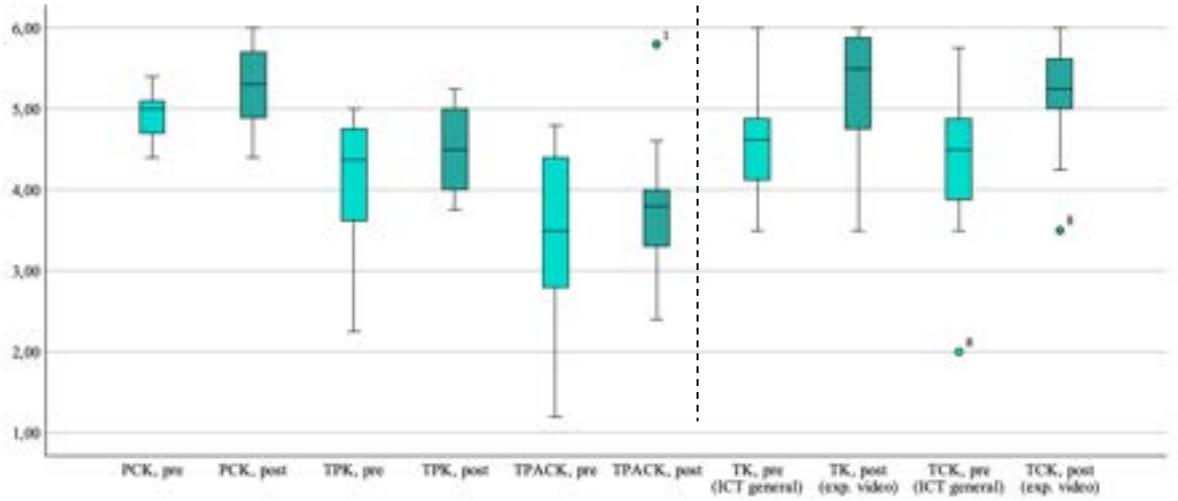
Participation was voluntary and anonymous. The average age of the participants was 39.6 years (SD = 5.9 years), with an average of 13.4 years of professional experience (SD = 16.6 years).

Results

Professional Knowledge

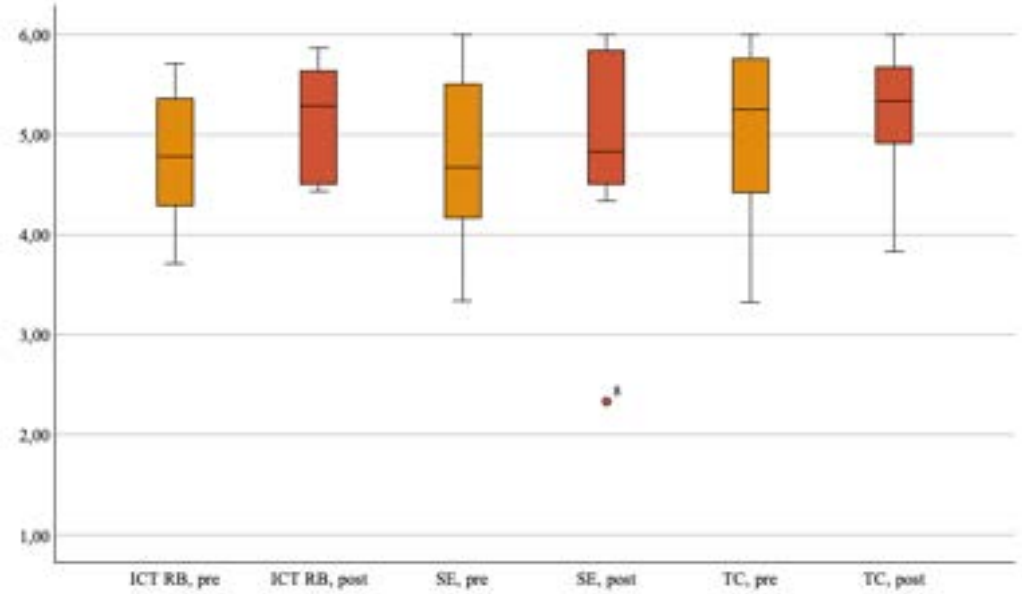
The following Figure 3 presents the results of the study for all TPACK dimensions.

Figure 3. Boxplots for TPACK dimensions, pre-test data (left) and post-test data (right).



A comparison of the pre-test and post-test values suggests a slight upward trend in most TPACK dimensions. PCK, TPK and TPACK show a slight improvement. The post-test values (relating to experimental videos) for TK and TCK are higher than the corresponding pre-test values (relating to ICT in general). Overall, the variance of the post-test scores is slightly lower compared to the pre-test scores.

Figure 4. Boxplots for ICT reaction beliefs (ICT RB), self-efficacy (SE) and technology commitment (TC), pre-test data (left) and post-test data (right).



The results shown in Figure 4 indicate that participation in the PD program led to a slight increase in participants' ICT reaction beliefs and self-efficacy, while the technology commitment remained largely at the same level. It can also be observed that the variance of the post-test data tends to be lower than that of the pre-test data.

The results of the comparison of the mean values between pre- and post-test confirm most findings (see Table 2). The small increase in the mean self-efficacy score could be attributed to the presence of an outliner in the data (see Figure 4).

Table 2. Overview of the pre- and post-test mean values of all constructs.

Construct	Mean Value, Pre	Mean Value, Post
Pck	4.90 (Sd = 0.31)	5.28 (Sd = 0.51)
Tpk	4.08 (Sd = 0.92)	4.50 (Sd = 0.54)
Tpack	3.47 (Sd = 1.09)	3.80 (Sd = 0.86)
Tk	4.60 (SD = 0.76), ICT General	5.23 (SD = 0.79), Exp. Video
Tck	4.31 (SD = 0.95), ICT General	5.15 (SD = 0.71), Exp. Video
Ict Rb	4.79 (Sd = 0.67)	5.14 (Sd = 0.57)
Se	4.78 (Sd = 0.87)	4.94 (Sd = 1.05)
Tc	5.07 (Sd = 0.87)	5.21 (Sd = 0.69)

The analysis of the qualitative data has not yet been completed.

Discussion

The present study aimed to investigate the impact of an in-service teacher PD program addressing learning with (interactive) experimental videos on teachers' professional knowledge as well as on their ICT-related beliefs. Comparing pre- and post-test data, slightly positive tendencies were observed in selected TPACK dimensions, for ICT reaction beliefs and for self-efficacy. In contrast, no increase was identified for technology commitment. For this construct, the post-test score remained approximately at the same level as before participating in the PD program.

The designed PD program aimed to enhance teachers' competencies in using domain-specific ICT, specifically (interactive) experimental videos. During the PD program, participating teachers engaged intensively with this domain-specific ICT and acquired fundamental skills for the independent production of such media. As a result, teachers rated their TK and TCK regarding the specific medium '(interactive) experimental video' higher after participating in the PD program than they had prior to participation regarding digital media in general. Moreover, positive tendencies were observed for PCK, TPK and TPACK. These findings are consistent with further studies reporting positive effects of targeted interventions on professional knowledge (within the TPACK framework), both for pre-service teachers (Stinken-Rösner et al., 2023) and in-service teachers (Lehiste, 2015). In particular, the results demonstrate that practice-oriented PD programs can make a substantial contribution to teacher professionalization.

One key element of the PD program is the implementation of (interactive) experimental videos in the student lab, where participating teachers gain experience in using these videos with their own class. During this implementation phase, teachers were able to observe students' interactions with the (interactive) experimental videos and thereby identify their potential for effectively conveying domain-specific content as well as domain-specific language (through adding a voice-over to an experimental video). We hypothesized that an embedded implementation phase would be an opportunity to positively affect teachers' beliefs about the use of digital media. Positive tendencies for ICT reaction beliefs and self-efficacy were found, with the increase in self-efficacy being marginal. Furthermore, no change in technology commitment could be observed (see

Figure 4). This finding is not entirely consistent with previous research reporting a medium effect of general PD programs on STEM teachers' self-efficacy (e.g., Zhou et al., 2023). This discrepancy may be related to the PD program itself. It was both domain- and media-specific, whereas teachers' self-efficacy was assessed in the questionnaire with respect to the utilization of digital media in general. Consequently, the small increase in general self-efficacy suggests that the domain-specific focus of the program was not reflected in overall self-efficacy beliefs. However, this does not preclude the possibility that teachers' domain- and media-specific self-efficacy increased more strongly because of the program.

Furthermore, observing students working effectively with (interactive) experimental videos may explain the increase in ICT reaction beliefs. Thus, teachers perceived (interactive) experimental videos as effective and meaningful digital tools for physics lessons. However, this would also suggest an increase in technology commitment, which is not indicated by the data. One possible explanation may lie in the independent production of (interactive) experimental videos, which several participants perceived as time-intensive during the program. This may represent a potential implementation barrier. Also, these outcomes suggest that technology commitment can be regarded as a relatively stable construct. So, the targeted promotion may require long-term interventions, as stated by Lipowsky and Rzejak (2021). In this context, no generally valid appropriate time frame can be specified, as the assessment of appropriateness depends on a wide range of factors, such as individual prerequisites of the participating teachers or specific focus of the PD program (Lipowsky & Rzejak, 2021). In addition, one can identify that the scales used to assess the teachers' beliefs were utilized to a high degree (see Figure 4), meaning that the presence of potential ceiling effects cannot be ruled out.

Limitations

When interpreting the results, several limitations need to be considered. Firstly, the present study concerns a small sample size with only 12 physics teachers. Therefore, the generalizability of the results is limited. Consequently, future research with larger samples is needed to examine the reported effects. Secondly, the study relies on self-assessed measures of professional knowledge, which may not accurately reflect teachers' actual levels of competence. As self-assessed competencies do not fully correspond to objectively measured professional knowledge (Stinken-Rösner et al., 2023), future research should incorporate performance-based measures to more comprehensively assess teachers' professional knowledge. Finally, the transferability of the results to school practice needs to be critically assessed. In this context, instructional actions were conducted under conditions that differ from regular school practice, in the learning environment, the availability of technical resources, and the instructional role. This role was assumed by a scientific staff member rather than the classroom teacher. Consequently, actual belief-related constructs may be lower than indicated in the post-test, as participating teachers may experience uncertainties when implementing (interactive) experimental videos in their own teaching practice. Therefore, future studies should include follow-up assessments to examine the development of teachers' self-efficacy in authentic school settings.

Conclusion

This study investigated the impact of an in-service teacher PD program focusing on learning with (interactive) experimental videos on physics teachers' professional knowledge (TPACK) and ICT-related beliefs. The findings indicate that the designed PD program slightly positively influences selected dimensions of teachers' professional knowledge, their ICT reaction beliefs, as well as their self-efficacy. However, no changes were observed in teachers' underlying technology commitment. Two main conclusions emerge from the findings. First, digitalization-

related, domain-specific PD programs have the potential to foster teacher professionalization. Second, an implementation phase in which the domain-specific medium is tested may represent a condition to successfully initiate changes in teachers' beliefs. In this context, it is assumed that the time-intensive production of (interactive) experimental videos may constitute a potential barrier. To further investigate these assumptions, the data obtained from the interviews regarding conditions for success and barriers to the implementation of ICT, particularly (interactive) experimental videos, will be analysed in future work.

Acknowledgement

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Navigating Digital STEM Professional Development: Insights From Out-Of-School Labs

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The demand for high-quality teacher professional development (PD) is significant, especially in the context of a digitalised world. Effective PD fosters collaborative work, self-efficacy and student-centred approaches. In this context, PD programmes that take place in out-of-school labs or are closely linked to them in various ways offer great potential that has not yet been realised. The ministry-funded research project "LFB-Labs-digital" investigates this potential in Germany by taking eight STEM out-of-school labs as venues for PD in teachers' information and communication technology (ICT) skills. An accompanying interdisciplinary quality management captures, among other things, the expectations and perceptions of the participating teachers regarding the PD programmes. The study explores these aspects as well as teachers' perceived relevance, cognitive activation, and the sustainability of the implementation of PD content. Data was collected from 83 teachers in pre-surveys and 48 teachers in post-surveys across eight out-of-school labs. Pre-survey results indicate that teachers primarily demand subject-specific digital media use, the application of specialized software, and guidance on designing digital learning environments. Teachers consider the PD programmes relevant when it offers feasible implementation, manageable workload, and curriculum relevance. Post-survey results show positive perceptions of PD programmes' perceived relevance, cognitive activation, and sustainability regarding digital teaching. The data shows promising potential for the approach of out-of-school lab-based teacher PD across multiple STEM subjects.

Keywords: digital learning, teacher education, professional development

Introduction

Due to ongoing digitalisation worldwide, the development of digital competencies is more important than ever in society and is therefore a core topic of the European Union's Digital Education Action Plan (European Commission, 2023). As the development of students' digital competencies largely depends on teachers' instructional practices, there is a particular need for professional development (PD) targeting teachers' information and communication technology (ICT) skills (OECD, 2019). Teachers must not only possess digital competencies themselves but also give their students possibilities to improve these skills. Added to this is subject-specific knowledge required in the classroom, so that teachers are faced with multifaceted requirements: the integration of technological, pedagogical and content knowledge (TPACK) (Mishra & Koehler, 2006). The continuous development of relevant competencies must be a cornerstone of teacher education and PD (Eickelmann et al., 2019).

While offering ICT-related PD for teachers is highly relevant due to deficits with regard to ICT training among teachers (Eickelmann et al., 2019; Fernandes et al., 2020; Fernández-Batanero et al., 2022), implementation and evaluation is challenging in many countries (Popova et al., 2022). Despite high demand, comparatively low participation rates in PD are observed (Popova et al., 2022). Another problem is that many PD programmes are conducted as so-called one-shot events (Fernandes et al., 2020), although research indicates longer-term programmes being more sustainable regarding positive effects on students (Lipowsky & Rzejak, 2015). These challenges are also evident in Germany (Mußmann et al., 2021), even though the national Conference of Ministers of Education and Cultural Affairs strongly emphasises the importance of digital media (Kultusministerkonferenz, 2017).

In recent years, out-of-school labs and other non-formal learning environments have established themselves as innovative extracurricular learning opportunities for students (Kirchhoff et al., 2022). They provide a unique setting where students can gain authentic practical experience and apply scientific concepts, potentially increasing interest and motivation in STEM subjects (Itzek-Greulich & Vollmer, 2017; Mohr-Schroeder et al., 2014; Roberts et al., 2018). These characteristics present promising potential to use these out-of-school learning environments as venues for PD related to digitalisation. This potential has been empirically examined by Reher et al. (2025), who found positive effects of digitalisation-related PD in out-of-school labs on teachers' self-assessed professional knowledge, while belief-related dimensions such as self-efficacy and technology commitment remained largely stable.

Within the same project, complementary analyses have focused on success factors and implementation barriers of these PD programmes (Lüsse et al., 2025). This research identifies factors such as technical support, curricular alignment, hands-on orientations, and structured reflection as potential success conditions, alongside persistent organisational and technical challenges. However, this research has primarily focused on the perspectives of PD facilitators or on external observations of programme implementation. The perspectives of teachers as the users of these PD programmes, particularly with regard to how they perceive and evaluate digitalisation-related PD in out-of-school lab settings, remain underexplored.

Addressing this research gap, the present study focuses explicitly on teachers' perspectives on digitalisation-related PD programmes conducted in out-of-school labs. The study examines teachers' needs and expectations prior to participation and investigates how participating teachers perceive the relevance, cognitive activation, and sustainability of the PD programmes with respect to digitalisation-related aspects. By adopting the users' perspective, the study aims to contribute to a more differentiated understanding of the potential and limitations of out-of-school labs as venues for effective and sustainable teacher PD.

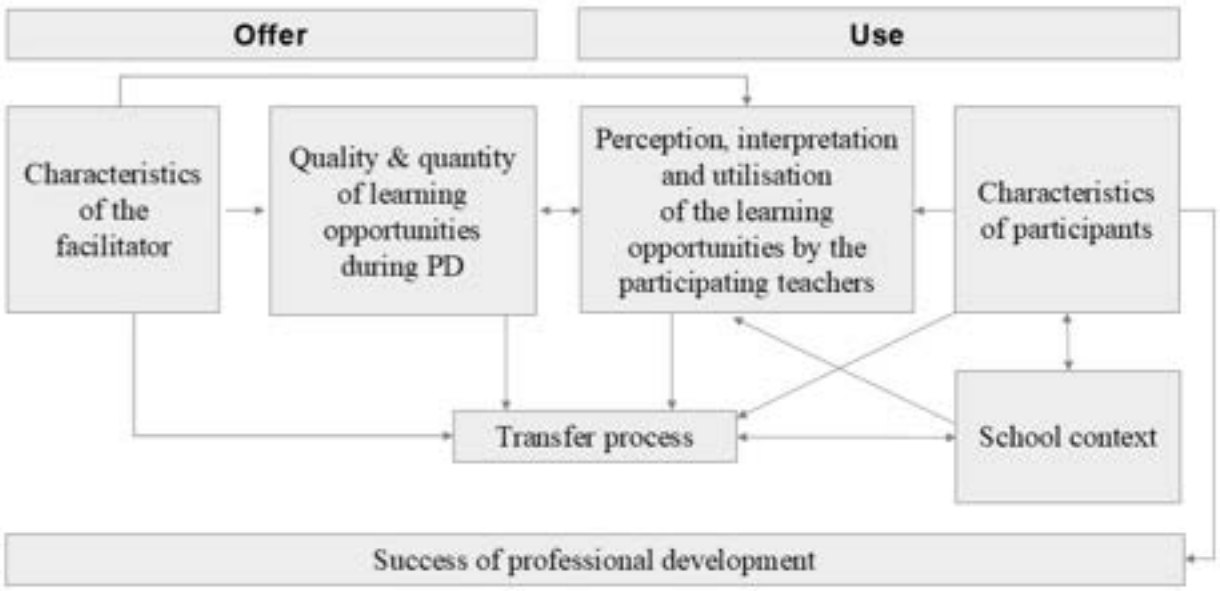
Theory And State Of Research

Key Features Of Effective Professional Development

To illustrate the multifactorial transfer processes and influencing factors in PD, an adapted offer-and-use model by Lipowsky and Rzejak (2015) can be applied (Figure 1). The model conceptualises PD as an interaction between the offer side, referring to the design and implementation of PD programmes, and the use side, representing participating teachers with their individual prerequisites and school contexts.

On the offer side, relevant aspects include the professional expertise of facilitators as well as the quality, structure, and coherence of the learning opportunities provided. Empirical research has consistently shown that effective PD for STEM teachers is characterised by a strong focus on subject-specific content, pedagogical approaches, and the integration of technology into teaching and learning processes (Joseph & Uzondu, 2024). Lipowsky and Rzejak (2015) also identify essential characteristics of effective PD, including the integration of input, trial, and application phases, as well as creating situations where teachers experience self-efficacy and focus on student learning within professional learning communities. These principles, including inquiry-based and collaborative learning, also apply to ICT-related PD programmes (Fernandes et al., 2020).

Figure 1: Offer-and-use model for research on teacher PD (adapted from Lipowsky & Rzejak, 2015, p. 30).



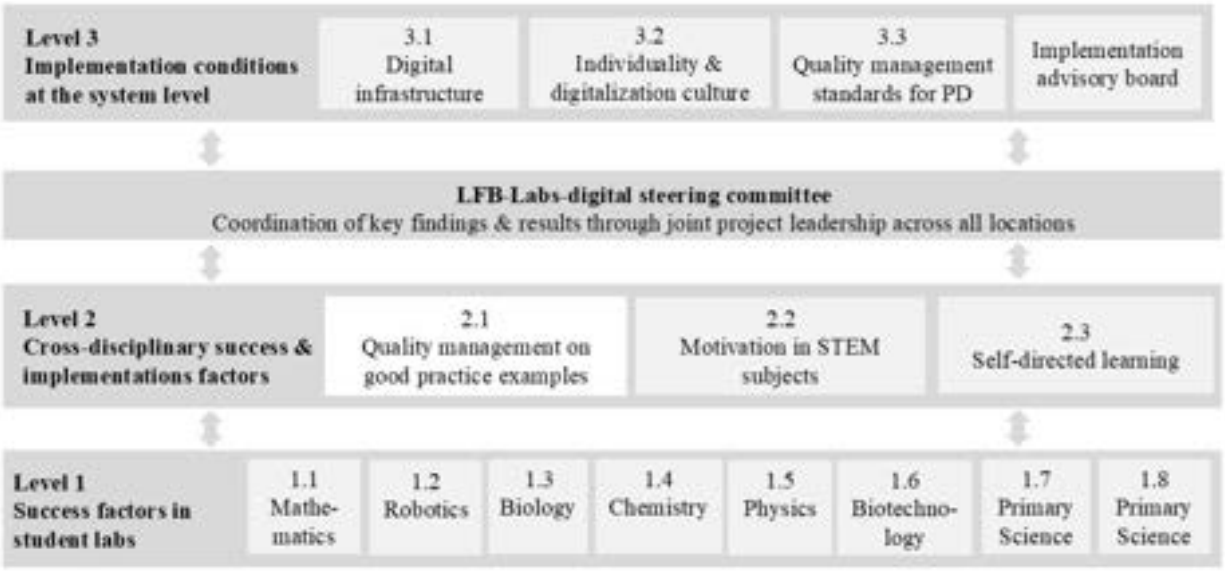
Beyond these general features, recent empirical studies have begun to specify conditions for effective PD in non-formal learning environments such as out-of-school labs. Focusing on digitalisation-related PD in such contexts, Lüsse et al. (2025) identified technical support, curricular alignment, flexible formats, hands-on orientations, peer exchange, and structured reflection opportunities as potential key success factors for PD in out-of-school labs. These features support teachers in critically reflecting on and adapting digital tools and strategies for their own teaching practice. At the same time, the study highlights persistent technical and organisational challenges as well as heterogeneous digital competencies among teachers as implementation barriers. Together, these findings underline the importance of designing PD programmes that combine coherence and adaptability in order to address diverse teacher needs.

Context Of The Study

Against this theoretical and empirical background, the collaborative, ministry-funded project *LFB-Labs-digital* was initiated (Figure 2; Kirchhoff et al., 2024). The primary objective of this project is to establish out-of-school labs as innovative learning environments for digitally supported PD programmes. To achieve this, eight STEM-focused out-of-school labs in the state of North Rhine-Westphalia, Germany, are being adapted and expanded to serve as PD venues. These labs cover a range of disciplines, including Mathematics, Biology (two labs), Chemistry, Physics, Biotechnology, and Primary Science Education (two labs).

As part of the project, an interdisciplinary quality management approach accompanies the ongoing PD programmes. This involves systematic observation, continuous exchange with PD facilitators, and the identification and discussion of good practice examples across sites. Previous analyses conducted within the project context have examined PD programmes from the perspectives of facilitators and external observers, focusing on implementation conditions and barriers (Lüsse et al., 2025). However, the perspectives of teachers as the users of these PD programmes have not yet been systematically investigated.

Figure 2: Project structure of LFB-Labs-digital (adapted from Kirchhoff et al., 2024, p. 136).



Addressing this research gap, the present study focuses explicitly on the teachers' perspectives. The central research question is how teachers perceive the PD programmes. Initially, the needs and expectations of teachers regarding digitalisation-related out-of-school labs PD programmes will be assessed. Furthermore, it will be examined how participating teachers evaluate the relevance, cognitive activation, and sustainability of the PD programmes concerning aspects related to digitalisation.

Method

The study combines qualitative feedback and quantitative surveys and was conducted via LimeSurvey. Participation in both the pre- and post-survey was voluntary. In the pre-survey, teachers were asked about their expectations and perception of relevance regarding the out-of-school lab PD programme using self-developed two open-ended items:

1. "In the PD programme, I would like to learn more about ... / I expect insights into ... from the programme."
2. "For me, a PD programme is relevant to my teaching if it…"

Table 1: Post-survey instrument.

	Relevance	Cognitive Activation	Sustainability
	3 Items α = .900	6 Items α = .910	6 Items α = .896
Example item	RelAd1: "In the PD programme, we talked about why the topic is important for digital teaching."	KogA2: "In the PD programme, we reflected on our professional practice regarding digital teaching."	Nach4: "In the programme, we discussed how the PD content on digital teaching can be implemented at our schools."
Measurement	Post-Survey: 6-point Likert scale from 1 = strongly disagree to 6 = strongly agree		

In the post-survey, validated six-point Likert scales developed by Rzejak et al. (2023) were shortened and adapted to the context of digital learning. These scales assessed teachers'

perceptions of relevance, cognitive activation, and sustainability after participating in the PD programme (Table 1). The post-survey was administered immediately after the PD programme.

The open-ended responses were analysed using content analysis (Kuckartz, 2018). An inductive category system was developed and subsequently discussed, revised, and refined in collaboration with two additional research associates. The resulting category system was then validated using the AI Assist tool in MAXQDA Analytics Pro (24.0.0), but no further modifications were deemed necessary.

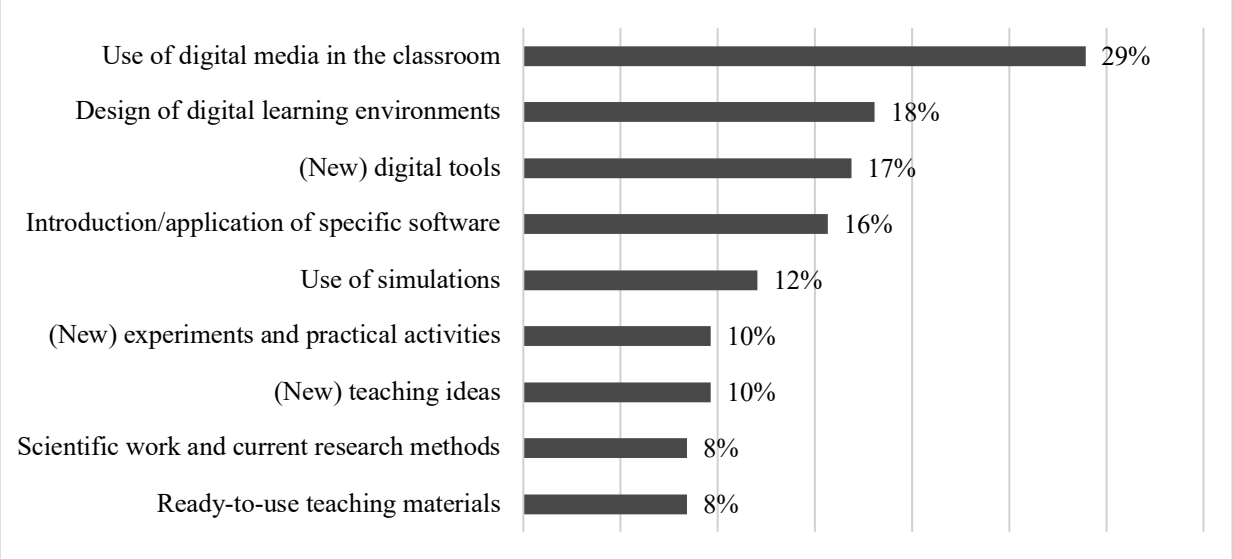
To analyse the quantitative data of the post-survey, descriptive statistics were applied. Additionally, potential changes in participants' evaluations across different PD programme iterations were examined in the context of the design-based research approach. Here, comparisons between the first and second iteration were conducted for PD programmes that were implemented more than once, as not all programmes were offered in multiple iterations. Given the ordinal scale level and small sample sizes, Mann-Whitney U tests were applied.

Results

Pre-Survey

Data was collected from 107 teachers (83 teachers in pre-surveys and 48 teachers in post-surveys) across all eight PD programmes. The results of the pre-survey indicate that teachers most frequently expected the aspects shown in Figure 3 from digitalisation-related PD programmes in out-of-school labs. In some cases, individual teachers' responses were assigned to multiple categories.

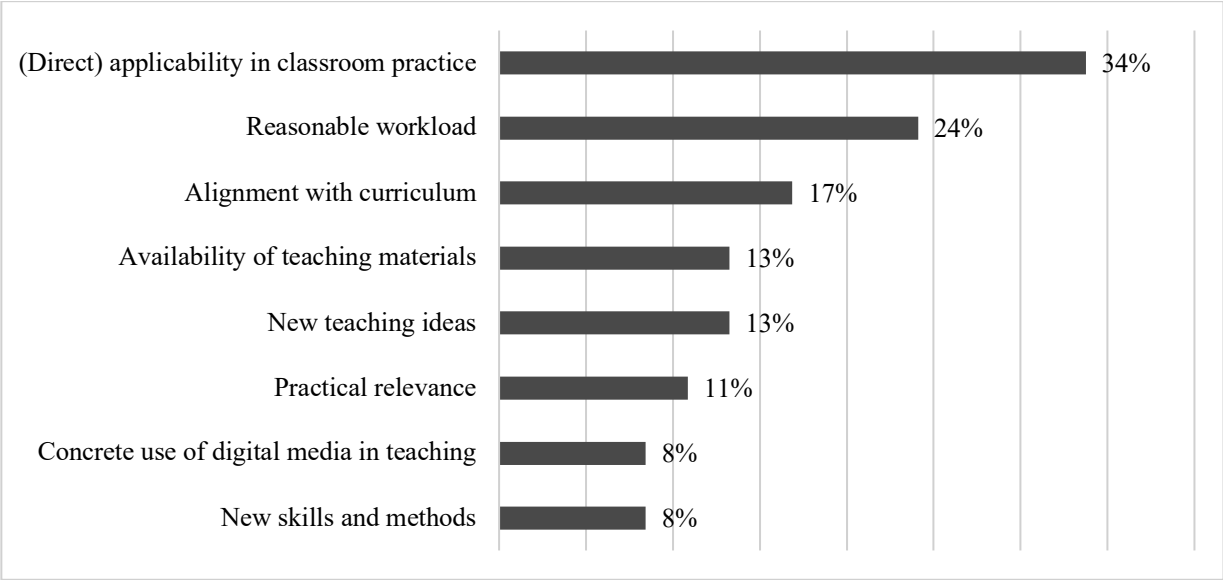
Figure 3: Most frequently expected aspects from digitalisation-related PD programmes in out-of-school labs mentioned by participating teachers (*n* = 83).



Among the most frequently mentioned expectations, many responses were related to digitalisation, e.g.: information on using digital media in the classroom (29%), designing digital learning environments (18%), and discovering new digital tools (17%). However, participants also expressed expectations that were not directly related to ICT, such as engaging in practical activities and (new) experiments (10%), exploring new teaching ideas (10%), engaging with scientific methods and current research practices (8%), and receiving ready-to-use teaching materials (8%).

In response to the question on relevance, the surveyed teachers stated that they consider a PD programme relevant to their teaching if it addresses the aspects shown in Figure 4.

Figure 4: Aspects that make a PD programme relevant to teachers (*n* = 83).



Across all topics, the most frequently mentioned criterion for relevance was that the PD content should be directly applicable to classroom practice (34%), and that it should involve a reasonable amount of time and effort (24%). Teachers also emphasized that content should be aligned with the curriculum (17%) and offer real-world or practical relevance for students (11%). Additional aspects mentioned included the desire for new teaching ideas (13%) and opportunities to learn new skills and methods (8%). As already seen in the expectations, teachers considered a PD programme to be relevant if it provided ready-to-use teaching materials (13%) and gave practical guidance on how to implement digital media in the classroom (8%). A few teachers also mentioned aspects such as strategies for differentiated instruction (4%) and opportunities for collegial collaboration (2%).

Post-Survey

In the Post survey, 48 teachers rated the relevance of programme regarding digital teaching with a mean value of $M = 4.78$ ($SD = 1.19$, $\alpha = .900$) on a scale range from 1 for negative perception to 6 for positive perception. Cognitive activation regarding digital teaching was scored with a mean value of $M = 4.02$ ($SD = 1.26$, $\alpha = .910$) and sustainability regarding digital teaching with a mean value of $M = 4.62$ ($SD = 1.13$, $\alpha = .896$) on the same scale range.

The PD programmes in the subjects of Mathematics, Chemistry, Physics, and Biotechnology were each conducted more than once. Table 2 presents the descriptive post-survey results for the three evaluated scales for the first and second iteration of these PD programmes.

Table 2: Post-survey results of the PD programmes with more than one iteration: Mathematics, Chemistry, Physics, and Biotechnology.

	First Iteration (n = 19)		Second Iteration (n = 33)	
	M	*SD*	*M*	*SD*
Relevance	4.67	1.26	4.96	1.02
Cognitive Activation	3.68	1.23	4.33	1.22
Sustainability	4.64	0.93	4.86	0.98

To examine whether these observed differences between the two PD iterations were statistically significant, Mann-Whitney U tests were conducted for each of the three scales. The comparison revealed no statistically significant difference in perceived relevance between the first and second

iteration (U = 282.00, Z = -0.606, p = .545). Similarly, ratings regarding sustainability did not differ significantly between the two iterations (U = 273.00, Z = -0.772, p = .440). For cognitive activation, the difference did not reach statistical significance but showed a trend toward higher ratings in the second iteration (U = 212.50, Z = -1.923, p = .054).

Discussion

Initial insights of the pre-survey demonstrate that effective PD for teachers must balance theoretical knowledge with practical applicability, which is consistent with findings of other studies (Darling-Hammond et al., 2017; Rzejak et al., 2023). Additionally, teachers demand subject-specific digital tools, digital learning environments, and use of specific software. From a theoretical perspective, the pre-survey results contribute to existing research on PD by highlighting the importance of subject-specific digital competence training (Mishra & Koehler, 2006). The findings further underscore the need for continuous professional learning in digital environments that are closely connected to authentic, practice-oriented learning settings. These findings support the growing body of literature on TPACK and its role in effective teaching in the digital age (Fernandes et al., 2020; Thoms et al., 2022). Additionally, the results provide insights into the user side of PD, capturing aspects such as the perception, interpretation, and utilisation of the offered learning opportunities (Lipowsky & Rzejak, 2015). In this regard, the findings underline the relevance of teachers' subjective relevance judgements for understanding PD effectiveness, as design features alone may not determine how learning opportunities are perceived and taken up.

The scales used in the post-test, adapted from Rzejak et al. (2023), have shown to be a suitable instrument for evaluating the perceived relevance, cognitive activation, and sustainability of out-of-school labs related PD regarding digital aspects. The positive trend in the results provides initial indications that the expectations of teachers on the offer side could be addressed. In particular, the descriptively higher ratings observed in the second iteration, especially with regard to cognitive activation, may point towards iterative improvements within the design-based research process, although these differences did not reach statistical significance.

However, the findings need to be interpreted with caution. First, the results are based on teachers' self-reports and rely on relatively small sample sizes, which limits the generalisability of the findings. Second, the use of open-ended items in the pre-survey constitutes a further limitation. Teachers were likely to articulate only one or two aspects they perceived as most important, while other potentially relevant dimensions remained unmentioned. As a result, aspects such as collegial collaboration appear only marginally in the resulting category system, although they are well established in the literature as important features of effective PD (Lipowsky & Rzejak, 2015; 2021). This should therefore not be interpreted as a lack of relevance, but rather as an effect of prioritisation processes in teachers' spontaneous responses.

Conclusion And Outlook

In conclusion, this study provides insights into teachers' perceptions of digitalisation-related PD programmes conducted in out-of-school labs. The findings show that participating teachers particularly value PD formats that combine subject-specific digital tools with practical applicability and curricular relevance. Overall, the participating teachers reported positive perceptions of the PD programmes with regard to relevance, sustainability, and cognitive activation. However, cognitive activation was rated comparatively lower, indicating a potential area for further development.

By explicitly focusing on the teachers' perspective, this study extends previous research on PD in out-of-school labs, which has predominantly addressed design features and facilitator

perspectives (Lüsse et al., 2025). The results underline the importance of teachers' subjective relevance judgements in understanding PD effectiveness, thereby supporting the offer-and-use model of PD. Moreover, the descriptively higher ratings observed in the second implementation cycle suggest that iterative refinements within a design-based research approach may contribute to perceived improvements in PD quality. Due to the limited number of participants, this assumption needs further research.

Taken together, the findings highlight the potential of out-of-school labs as innovative learning environments for digitally supported teacher PD, particularly when PD offers are closely aligned with teachers' professional needs and classroom realities.

Looking ahead, several areas warrant further investigation. Future research should examine the longer-term impact of such PD programmes, particularly regarding the transfer of acquired digital competencies into classroom practice. Furthermore, as highlighted by Lipowsky and Rzejak (2015), the role of PD facilitators deserves closer attention. Investigating facilitators' perspectives, professional backgrounds, and attitudes towards digitalisation may provide valuable insights into factors influencing PD effectiveness.

Acknowledgement

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Assessing The Impact Of Lesson Study-Based Professional Development On Spatial Skills Of Primary Students

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This study evaluates a structured professional development (PD) program aimed at enhancing primary students' spatial ability by equipping teachers with targeted instructional strategies. As the final cycle of a design-based research (DBR) framework, it assesses student outcomes to determine PD effectiveness. The PD program, implemented through lesson study, guided 24 teachers in integrating spatial reasoning into STEM instruction using hands-on activities, visualization tasks, and spatial problem-solving exercises. Pre- and post-tests administered to 345 students in grades 1–3 showed significant gains, particularly in spatial visualization, followed by mental transformation and spatial orientation. Findings highlight the effectiveness of PD in fostering spatial ability and underscore the need for structured spatial ability instruction in early STEM education.

Keywords: Spatial ability, professional development, primary education

Introduction

This study examines the impact of a structured professional development (PD) program on enhancing primary school students' spatial ability by supporting teachers in integrating spatial ability into instruction. As the final cycle of a design-based research framework, it evaluates student outcomes as a measure of PD effectiveness. Spatial ability—the capacity to visualize, manipulate, and reason about objects in space—is a critical cognitive skill linked to success in STEM education (Uttal et al., 2013). Despite its importance, it remains underrepresented in primary curricula (Cheng & Mix, 2014). Research shows that PD programs focusing on spatial reasoning equip teachers with effective instructional techniques, such as hands-on activities, visualization tasks, and spatial problem-solving exercises (NRC, 2006). This study provides empirical evidence on how teacher PD improves student performance in spatial tasks, including mental transformation, spatial orientation, and spatial visualization, demonstrating the broader impact of targeted teacher training on STEM-related cognitive skills (Wai et al., 2009).

Theoretical Framework

This study explores the impact of PD on student learning and the role of spatial ability in STEM education. Using lesson study (LS) (Lewis et al., 2009) within a design-based research (DBR) framework, teachers collaborated to refine spatial reasoning lessons. The study applies the IMTP framework (Sims et al., 2023) to assess PD effectiveness through insights, motivation, techniques, and embedding practices. Results show that teachers deepened their understanding, improved instructional strategies, and enhanced student gains in mental rotation and spatial orientation. By linking teacher learning to student outcomes, this research highlights the value of structured, collaborative PD in fostering STEM-related skills.

Aim Of The Study

This study evaluates the impact of a structured teacher PD program on student spatial performance in primary STEM education. As the fourth cycle of a DBR project, it examines how improved instructional practices from LS translate into student gains, identifying which spatial components show the most and least improvement. Findings offer insights into the effectiveness of PD in fostering spatial ability in young learners by addressing the following research questions:

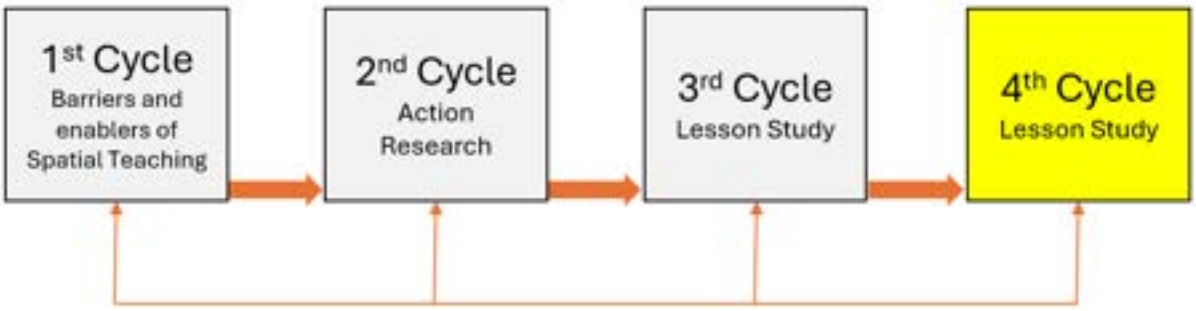
1.To what extent did students' spatial performance improve after teachers implemented the PD-based instructional strategies, as measured by pre- and post-test results?

2.Which spatial ability components (spatial visualization, mental transformation, spatial orientation) showed the most significant improvements, and which demonstrated the least change after the PD intervention?

Method

This study is part of a broader DBR project aimed at developing and refining a PD model to enhance spatial ability instruction in primary STEM education. Specifically, this paper reports on the fourth cycle of DBR, which focuses on evaluating the impact of the PD program on student spatial performance (see Figure 1). The study was conducted in two primary schools, involving 24 female teachers from grades 1–3 (with teaching experience ranging from 4 to 47 years) and their 345 students—104 first-grade students, 115 second-grade students, and 126 third-grade students. The PD program was designed to equip teachers with strategies for integrating spatial reasoning into STEM subjects, ensuring that the enhanced pedagogical practices translate into measurable student learning outcomes. The PD intervention followed a structured four-phase workshop model: (1) Reflection, where teachers analysed their current teaching practices; (2) Input and Modeling, where they explored core spatial ability components—spatial visualization, mental transformation, and spatial orientation—through expert-led activities; (3) Discussion, where collaborative engagement facilitated deeper pedagogical insights; and (4) Outcome Formulation, where teachers co-developed lesson plans incorporating spatial reasoning tasks. To embed these strategies into real classroom practice, the PD utilized a LS framework (Lewis et al., 2009), in which teachers worked in triads or groups of five to collaboratively design, implement, observe, and refine spatially enriched lessons for mathematics, science, and technology. This iterative process ensured systematic role rotation, promoting shared learning and continuous instructional improvement. To measure the impact of the PD program on student spatial performance, pre- and post-tests assessing key spatial ability tasks (e.g., mental transformation, spatial visualization, spatial orientation) were administered to the students of participating teachers. These tests provided quantitative evidence of changes in student performance, while teacher reflections and lesson study observations offered qualitative insights into how improved instructional practices influenced student learning. By systematically evaluating both student performance outcomes and teacher pedagogical growth, this study assesses the effectiveness of the designed PD model in enhancing spatial ability development in primary STEM education.

Figure 1. The Design-Based Research (DBR) process and the focus of the fourth cycle.



Findings

Findings For Research Question 1

A dependent t-test (paired t-test) was conducted for each grade level to compare students' pre- and post-test spatial performance scores. The results indicate a statistically significant improvement in spatial ability across all three grade levels. Below is a summary of the findings:

Table 1. Summary of Pre- and Post-Test Spatial Performance Scores Across Grade Levels,

Grade Level	Mean (Pre)	SD (Pre)	Mean (Post)	SD (Post)	t (df)	p-value	Significance
1st Grade	18.67	2.76	20.88	2.4	5.88	< .00001	Significant
2nd Grade	17.76	3.30	20.32	2.47	6.99	< .00001	Significant
3rd Grade	11.63	3.79	14.94	4.80	7.56	< .00001	Significant

*p < 0.05. SD: Standard deviation

All p-values are below the significance threshold ($p < .05$), indicating that the observed improvements in spatial ability are unlikely to be due to chance.

- First Grade: Students showed a significant improvement in spatial test performance after their teachers implemented PD-based instructional strategies ($M_{pre} = 18.67$, $SD = 2.76$; $M_{post} = 20.88$, $SD = 2.40$). The paired t-test yielded $t(104) = 5.88$, $p < .00001$, confirming a statistically significant increase.
- Second Grade: A notable improvement was also observed among second-grade students ($M_{pre} = 17.76$, $SD = 3.30$; $M_{post} = 20.32$, $SD = 2.47$). The dependent t-test result of $t(115) = 6.99$, $p < .00001$ supports the effectiveness of the instructional intervention.
- Third Grade: Students in third grade exhibited the most substantial improvement relative to their baseline scores ($M_{pre} = 11.63$, $SD = 3.79$; $M_{post} = 14.94$, $SD = 4.80$). The paired t-test analysis ($t(126) = 7.56$, $p < .00001$) confirms a significant positive shift in their spatial ability.

Findings For Research Question 2

This study also aimed to determine which spatial ability components (spatial visualization, mental transformation, spatial orientation) showed the most significant improvements after teachers implemented instructional strategies from the PD program. Since Grades 1 and 2 used the same test, the analysis was conducted for these two groups, while Grade 3 was excluded due to a different test format. To evaluate improvements, a dependent t-test (paired t-test) was conducted for each spatial ability component within Grades 1 and 2. The results indicate that all three spatial ability components demonstrated statistically significant improvements ($p < .05$) following the intervention. However, the degree of improvement varied across components as illustrated in table 2.

Table 2. Summary of Pre- and Post-Test Results for Spatial Ability Components in Grades 1 and 2.

Grade	Spatial Ability Component	Mean (Pre)	SD (Pre)	Mead (Post)	SD (Post)	t (df)	p-value	Significance
1st Grade	Spatial Visualization	6.21	1.21	7.13	1.05	5.73	<.00001	Significant
	Mental Transformation	6.43	1.25	7.11	0.96	4.74	<.00001	Significant
	Spatial Orientation	6.00	1.34	6.70	1.15	4.25	<.00001	Significant
2nd Grade	Spatial Visualization	5.95	1.28	6.73	1.12	6.10	<.00001	Significant
	Mental Transformation	6.14	1.43	6.90	1.08	5.79	<.00001	Significant
	Spatial Orientation	5.67	1.59	6.71	1.17	7.31	<.00001	Significant

Spatial visualization showed the greatest improvement across both grades, with first graders increasing from $M = 6.21$ to $M = 7.13$ ($t = 5.73$, $p < .00001$) and second graders from $M = 5.95$ to $M = 6.73$ ($t = 6.10$, $p < .00001$), indicating the strongest effect of PD-based strategies on spatial visualization. Mental transformation also showed substantial gains, with first graders improving from $M = 6.43$ to $M = 7.11$ ($t = 4.74$, $p < .00001$) and second graders from $M = 6.14$ to $M = 6.90$ ($t = 5.79$, $p < .00001$), though effect sizes were slightly lower than for spatial visualization. Spatial orientation showed the least improvement but remained significant, with first graders increasing from $M = 6.00$ to $M = 6.70$ ($t = 4.25$, $p = .00005$) and second graders from $M = 5.67$ to $M = 6.71$ ($t = 7.31$, $p < .00001$), suggesting a relatively stronger initial ability in this area, leading to smaller gains compared to the other two components.

Discussion

The significant gains in pre- to post-test scores highlight the effectiveness of structured PD interventions in enhancing students' spatial reasoning, a key skill for STEM learning and problem-solving (Newcombe, 2010). RQ1 findings indicate that students in Grades 1–3 showed

significant improvements in overall spatial ability after PD-based instructional strategies were implemented, supporting research on the benefits of early and sustained spatial training (Wai, Lubinski, & Benbow, 2009). The success of these strategies is likely due to their emphasis on hands-on, visualization-based, and problem-solving approaches, which strengthen spatial cognition (Lowrie, Logan, & Ramful, 2017). RQ2 analysis of spatial ability components in Grades 1 and 2 revealed that spatial visualization showed the greatest improvement, followed by mental transformation, while spatial orientation exhibited the least change. The strong gains in spatial visualization align with studies on the cognitive benefits of explicit training in mental imagery (Taylor & Hutton, 2013), while improvements in mental transformation support evidence on the malleability of spatial skills in classroom instruction (Levine et al., 2012). The smaller gains in spatial orientation suggest either a higher initial proficiency or a focus on static rather than dynamic spatial tasks (Verdine et al., 2014).

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Shifting Teachers' Knowledge And Confidence For Engaging Students In Science Practices From A Program Designed By Scientists And Pedagogical Experts

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The Next Generation Science Standards (NGSS) in the United States call for engaging students in authentic science through the practices of scientists (NRC, 2013). One challenge to translating the NGSS into the classroom is the lack of resources and programs that model and feature the scientific practices. This study describes a 10-day teacher professional development (PD) designed by both science researchers and education experts. As part of the PD, teachers developed and implemented a classroom research project (CLRP) curriculum plan centered on authentic scientific practices in molecular biology and the unique contexts of their schools. Following implementation, teachers delivered a presentation of their curriculums and the impact of implementing the curriculum on their instructional practices. In this mixed-methods study, we sought to answer two research questions: 1) To what extent do teachers who implement CLRPs increase their knowledge about how to align their teaching practices to the NGSS? and 2) To what extent do teachers who implement CLRPs increase their skills to engage students in scientific practices in their classroom? The findings indicate that teachers can increase their knowledge and confidence for aligning their teaching practices to NGSS. In addition, teachers also increased their skills and confidence for engaging students in science practices, particularly developing and using models. This study highlights the potential of teacher PD programs to enhance teachers' understanding and incorporation of science practices into their instruction, thereby promoting more authentic science learning experiences for students.

Keywords: Science practices, professional development, teacher education

Introduction

The Next Generation Science Standards (NGSS) in the United States call for engaging students in authentic science through the practices of scientists (NRC, 2013). Authentic science in the classroom involves engaging students in investigations that seek to answer scientific questions in ways that closely approximate those of scientists (Crawford, 2012, p.113). Traditional teacher education programs do not require preservice teachers to engage in scientific research (Burgin, 2020). This puts secondary science teachers at a disadvantage as most teachers lack expertise in the day-to-day practices of scientists such that they effectively integrate these practices into their science curriculum (Davidson et al., 2022). In particular, teachers' lack of understanding about scientific models and modelling limits their ability to engage students in developing and using models in the classroom (Gilber & Justi, 2016).

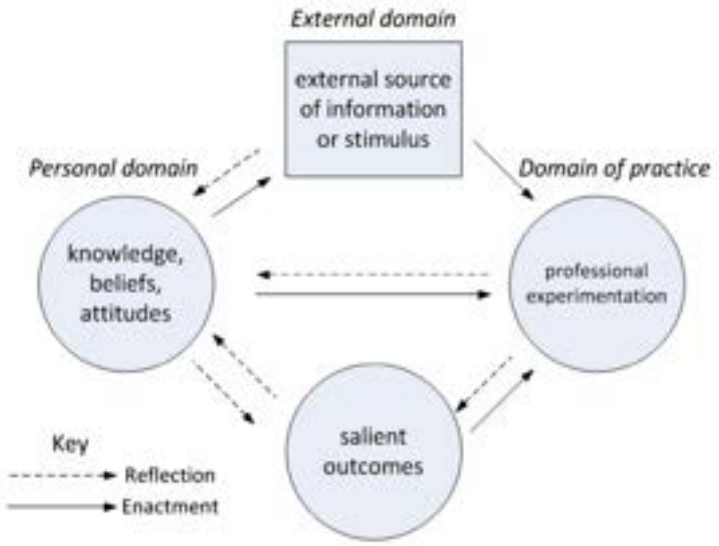
Successful implementation of high-quality instructional materials requires ongoing and sustained professional learning for teachers (Bybee & Chopyak, 2017). Biology curricular and instructional materials are loaded with visual representations and can be presented in a variety of ways (Dries et al., 2017). Yet, students are not explicitly taught how to interpret these representations and move between them as they are commonly used for exposure (Dries et al., 2017).

One strategy to increase teachers' knowledge of science practices and support the development and implementation of practices-based curriculum is to engage teachers in professional development (PD) involving both science education faculty and science research faculty.

Theoretical Framework

Clarke and Hollingsworth's (2002) teacher professional growth model served as the conceptual framework for designing the PD program and conducting this study (Figure 1), as it describes key elements for examining individuals or groups of teachers in the context of a particular PD program.

Figure 1. Clarke and Hollingsworth's (2002, p. 951) interconnected model of teacher professional growth.



Specific Aim And Research Questions

The program included a multi-disciplinary team with expertise from education, biochemistry, and medicine. The PD program was designed to engage high school biology and biochemistry teachers in molecular modelling science techniques and pedagogical strategies for classroom instruction.

The specific aim of the project was to create biomolecular science curriculum centred on authentic science practices. As part of a 10-day PD, teachers developed and implemented a classroom research project (CLRP) curriculum plan centred on authentic scientific practices in molecular biology and the unique contexts of their schools. Following classroom implementation, teachers delivered a presentation of their curriculum plans and the impact of implementing the curriculum on their instructional practices.

With this aim, we sought to answer two research questions:

1) To what extent do teachers who implement CLRPs increase their knowledge about how to align their teaching practices to NGSS?
2) To what extent do teachers who implement CLRPs increase their skills and confidence to engage students in scientific practices in their classrooms, with an emphasis on developing and using molecular models?

Methods

This mixed-methods study was designed to characterize teachers' understanding of science practices and how implementing their CLRPs increased their skills and confidence for engaging students in more authentic science practices.

Professional Development Program

The two-week summer PD program was designed to increase teachers' knowledge of the scientific practices, specifically *developing and using models*, *analysing and interpreting data*, and *communicating information*, involved in molecular biology research. The summer workshop was divided into three parts 1) content knowledge development, 2) research and design, and 3) curriculum development. During the content knowledge development portion of the workshop, teachers learned the fundamentals of protein folding, the technique of x-ray crystallography, and explored an example molecular story of insulin and diabetes. Teachers engaged in *modelling of* by using classroom molecular modelling kits. These kits were used to help build teachers' content knowledge, to map between a real molecule (insulin) and the representation being used, and to prepare teachers to engage in modelling for later in the workshop. Teachers engaged in *modelling for* through learning how the structures of proteins are determined using x-ray crystallography and how scientists make decisions based on data to generate a 3D model of a protein. Models generated from x-ray crystallography are published in a freely accessible public database, the Protein Data Bank (PDB). Using various PDB insulin files, teachers used JUDE, a molecular visualization program, to examine the active form of insulin, the monomer. Then, teachers looked at the dimer, and finally how insulin was stored as a hexamer. The workshop culminated with an open JUDE investigation looking at different designer insulins. Teachers worked in small groups to answer structure-function questions about how insulin was altered to control blood sugar in diabetes. Then, teachers transitioned to working with Penn State researchers to explore and develop a molecular story based on the work of Penn State research lab. The teachers developed a project poster and presented their findings at the workshop. Finally, in the curriculum development portion of the workshop, teachers collaborated with molecular biology researchers, science education faculty, and other participants in the cohort to develop a CLRP for their high school students around a protein of their choice.

Teacher Participants

Twenty-four teachers were recruited to participate in the program over three different cohorts. Teaching experience varied, with 42% of teachers reporting they had been teaching for 11 to 20 years. Teachers also indicated that they taught a range of subjects, the most common being biology (67%). Of the 24, 13 provided data pertaining to the implementation of their CLRPs.

Data Collection And Analysis

Multiple sources of data were collected for this mixed-methods study, including:

- Teacher surveys (CLRP survey)
- Teacher artifacts (CLRP documents and presentations slides)

Quantitative analyses of data collected from closed-ended survey items were conducted, including descriptive statistics and paired samples t-tests to determine whether the mean differences between participants' ratings from before to after implementation of the CLRP were statistically significant.

Qualitative analysis of teacher artifacts included a priori coding and comparative analysis. A priori coding involved applying predefined codes of the science practices to identify the presence of specific practices in their CLRPs (Creswell & Creswell, 2018) and implementation presentations. Open coding was conducted to identify shifts related to skills and confidence for engaging students in authentic science. Themes were identified using a thematic analysis approach (Clarke et al., 2015). The project team triangulated the findings from the various data sources.

Limitations

Several limitations exist in the study. Participating teachers self-selected to take part in the program, so the sample is skewed to teachers that are apt to participate in PD they chose, which limits generalizability to larger groups of teachers that do not select to participate in PD. In addition, we were only able to collect teacher-reported data, not the observations of implementation in the classroom.

Findings

Research Question 1

The teachers demonstrated knowledge of designing instructional plans for engaging students in science practices. In the CLRP documents, all teachers described how students would engage in molecular modelling practices to investigate a particular molecule (e.g., proteins, nucleic acid) of interest. Most teachers (67%) selected molecules for their CLRP that differed from those investigated during the workshop to attend to their students' interests and teaching context. This choice to explore other molecules indicates teachers' increased confidence in supporting students to use modelling practices to investigate molecules novel to teachers and students. Teachers also integrated the CLRP activities into their existing curriculum to provide scaffolding, align with state-level education standards, and incorporate molecular biology practices used by researchers.

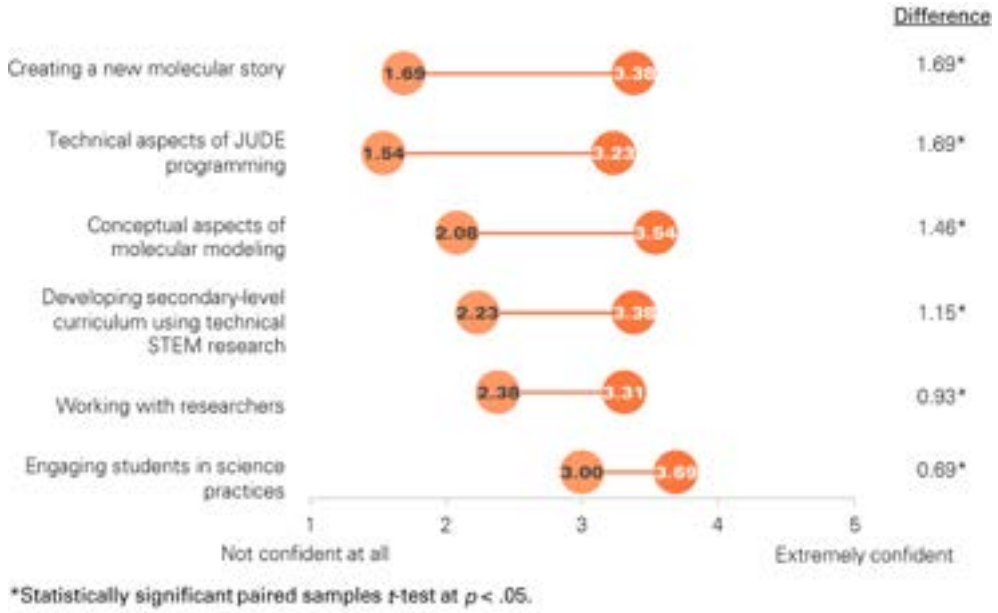
Teachers reported increased knowledge in the three target NGSS science practices after implementing their CLRPs relative to before implementation (Figure 2). Their self-rated knowledge about all three practices increased from before to after the CLRP implementation, particularly regarding developing and using models. The mean differences between their pre- and post- ratings were all statistically significant based upon the results of the paired sample t-tests.

Figure 2. Teachers' self-rated knowledge in target NGSS science practices before and after implementing the CLRPs in Years 2, 3, and 4 (n=13).



Teachers also reported increased confidence in various techniques and teaching practices after implementing their CLRPs (Figure 3). Their self-rated confidence in all areas increased from before to after their CLRP implementation, particularly in their confidence in creating a new molecular story and the technical aspects of JUDE programming. The mean differences between their pre- and post-ratings were all statistically significant based on the results of paired samples t-tests.

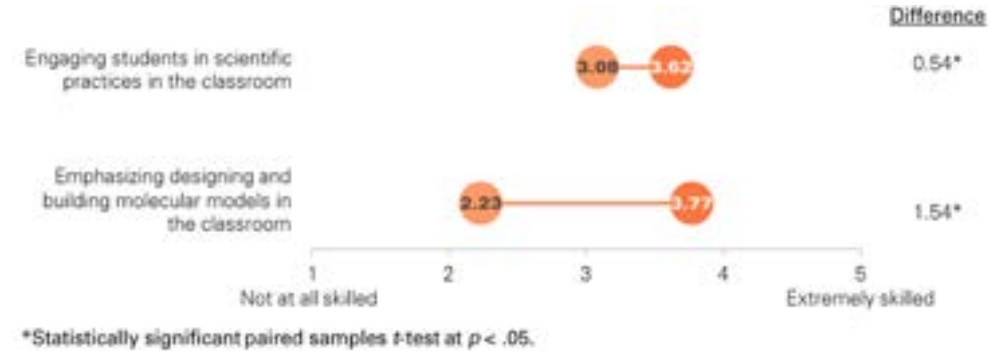
Figure 3. Teachers' self-rated confidence before and after implementing the CLRPs in Years 2, 3, and 4 (n=13).



Research Question 2

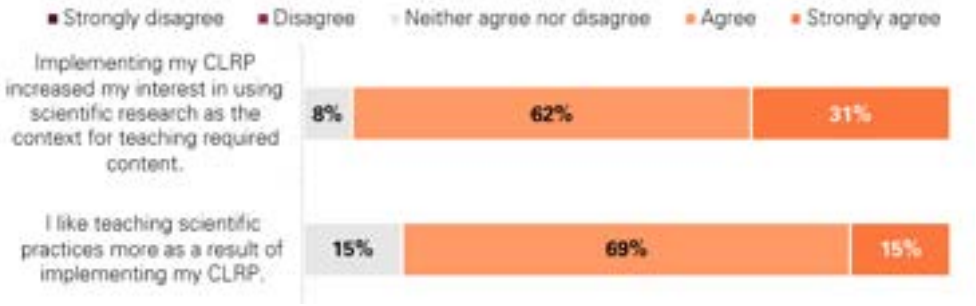
Teachers reported increased skills to engage students in scientific practices and molecular modeling after participating in the CLRPs relative to before (Figure 4). After implementing their CLRPs, teachers rated their skills in engaging students in scientific practices and molecular modeling before and after implementation. Their self-rated skills increased from before to after the CLRP implementation, particularly their skills in emphasizing designing and building molecular models in the classroom. The mean differences between their pre- and post-ratings were all statistically significant based on the result of paired sample t-tests.

Figure 4. Teachers' self-rated skills in engaging students in scientific practices and molecular modeling before and after implementing the CLRPs in Years 2, 3, and 4 (n=13).



After implementing their CLRPs, teachers rated the extent to which implementing their CLRPs increased their interest in and enjoyment of using scientific research and practices in their teaching (Figure 5). Most teachers agreed (62%-69%) or strongly agreed (15%-31%) with these statements, indicating that implementing the CLRPS not only increased teachers' skill in engaging students in scientific practices and molecular modelling, but also impacted teachers' interest in and enjoyment of using these practices in their teaching.

Figure 5. Teachers' ratings of the impact of implementing their CLRPs on their interest in and enjoyment of using scientific research and practices in Years 2, 3, and 4 (n=13).



In the post-implementation presentation slides, teachers identified specific NGSS science practices that students engaged in during the CLRP. All of the teachers described engaging students in developing and using models along with other science practices (e.g., asking questions, obtaining, evaluating, and communicating information). However, the practice of analysing and interpreting data was not mentioned. Multiple teachers described the challenges of scaffolding the learning of reading and understanding research papers and programming in JUDE to create 3-D visualizations of molecules.

Discussion And Implications

One of the key insights from this study is that sustained professional development can increase teachers' knowledge of and confidence for aligning their teaching practices with NGSS standards. With PD designed to engage teachers in current science practices and support their development of practices-based curriculum appropriate for their teaching context, teachers successfully incorporated science practices into their existing curriculum plans and identified molecules of interest relevant to their specific teaching situations. This alignment between NGSS standards and classroom implementation is particularly evident in teachers' adoption of the scientific practices—a central component of the three-dimensional learning framework outlined in NGSS. Consistent with Capps and Crawford (2013), sustained PD can help teachers to better understand these scientific practices and translate standards into meaningful classroom experiences.

The study revealed that teachers increased their skills and confidence for engaging students in science practices, particularly in developing and using models. This finding is unsurprising given that modeling was the central practice explored throughout the workshop. The depth of teachers' self-reported implementation and the transfer to their unique teaching contexts demonstrates meaningful learning. Our study supports the findings of Justi and Gilbert (2002) in that teachers identified the substantial scaffolding required for students to engage authentically in the developing and using models practice in molecular biology. We also found that teachers reported a high degree of interest and enjoyment in using scientific research and practices in their teaching. This positive affective response aligns with findings from Kreifels et al. (2021), who found that teachers participating in a 12-month inquiry-based learning professional development program developed increased confidence, possessed positive attitudes toward implementation, and felt that barriers could be controlled. Such affective outcomes are particularly important, as teacher confidence and interest often predict sustained implementation of new instructional approaches (Desimone, 2009).

The study also revealed teachers increased their skills and confidence for engaging students in science practices (Davidson et al., 2022), particularly *developing and using models* (Gilber & Justi, 2016). While teachers identified the challenges of scaffolding required for students to engage in these practices, the teachers reported a high degree of interest and enjoyment for using scientific research and practices in their teaching.

Several directions for future research emerge from this work. First, longitudinal studies are needed to examine whether teachers' increased confidence and skills in implementing science practices persist over time and become embedded in their regular instructional routines. Second, future research should investigate student learning outcomes associated with teachers' implementation of practices-based instruction following this type of PD. While teacher knowledge and confidence are important intermediate outcomes, the ultimate goal is enhanced student understanding of both disciplinary core ideas and the nature of scientific inquiry. Third, research is needed to identify the specific components of the PD model that were most effective in promoting teacher learning and implementation. Understanding which elements, whether the authentic research context, sustained duration, collaborative curriculum development, or other factors, most strongly influence outcomes would allow for more efficient and targeted PD design. Finally, exploring how this model might be adapted for teachers in different contexts (e.g., varying levels of resource availability, diverse student populations, different grade levels) would support broader dissemination and impact.

In conclusion, this study highlights the potential of carefully designed teacher PD programs to enhance teachers' understanding and incorporation of science practices into their instruction, thereby promoting more authentic science learning experiences for students. The findings suggest that when teachers engage directly in scientific practices within their own subject-matter contexts and receive sustained support for curriculum development, they can successfully align their instruction with NGSS standards and develop the confidence to implement challenging pedagogical approaches. Continued collaboration between science researchers and pedagogical experts is essential to bring such authentic science learning experiences to secondary classrooms at scale.

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Section: Lifelong Learning And Career Development For Science Teachers

ESERA 2025 Copenhagen

Science Teacher Educators In Professional Learning Communities: Exploring The Possibilities Of Creating New Organizational Routines

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One of the ways to support the professional development of science teachers in schools is through the establishment of professional learning communities (PLCs). But what about the professional learning of science teacher educators? The aim of this paper is to analyse and discuss the following two research question: How is it possible to organise professional learning communities for science teacher educators? How do science teacher educators experience their participation in such professional learning communities? We explore these questions building on an ethnographic study of a national program in science teacher education (NAFA) involving all science teacher educators in Denmark. We use a practice theoretical and Routine Dynamics perspective to understand how the new PLC-routines are created in the program. We identify some of the strengths and weaknesses of working together in this type of routines and discuss possible implications for the further development of professional learning communities for science teacher educators.

Keywords: Science Teacher Educators, Professional Learning Communities, Organizational Routines

Introduction

The purpose of this paper is to analyse and discuss how science teacher educators participate in professional learning communities. In the recent 30 years professional learning communities (PLCs) have become a certain way of organising professional collaboration in educational institutions worldwide (Albrechtsen et al., 2022; Lee et al., 2022; Moosa et al., 2024; Nguyen et al., 2024; Olsson, 2019; Sai & Siraj, 2015; Stoll et al., 2006). Beginning in North America in the 1990's and building on theories of the learning organization and organizational learning, the research primarily focused on school-based teacher collaboration. Since, the practice of and research on PLCs has expanded to also include other participants, like the whole school, the whole school district, research-practice partnerships and collaboration across educational organizations (Admiraal et al., 2021; Mundry & Stiles, 2009; Stoll & Louis, 2007). The interorganizational collaboration is also conceptualised as 'professional learning networks' (PLN) (Carpenter et al., 2022; Poortman et al., 2022; Prenger et al., 2021). Some research focusses on the more subject-specific parts of PLCs such as how they play a role in the professional development of science teachers (Blonder & Vescio, 2022; Dogan et al., 2016; Eylon et al., 2020; Jones et al., 2013; Vossen et al., 2020), but it is still limited how much we know about their significance for the professional development of science teacher educators. Science teacher educators are expected to develop different forms of knowledge (Mork et al., 2021) and strengthen their 'pedagogical content knowledge' (Hume et al., 2019), but how they share it with colleagues and how they build a 'pedagogy of teacher education' together (Loughran, 2006) is not something we know much about. We want to contribute with knowledge on how this is made possible in local PLCs and across organizational boundaries such as PLNs. These questions concerning the professional development of science teacher educators lie behind this paper presentation, but it can also be seen in the light of a more general and current interest in research on the professional learning of

teacher educators as our empirical data stem from the Danish teacher education system (Kelchtermans et al., 2018; Klink et al., 2017; Ping et al., 2018; Vanderlinde et al., 2021).

The empirical background is a 4-year longitudinal study (2022-2025) of an emerging interorganizational network of PLCs in the field of science teacher education in Denmark called *Naturfagsakademiet* (NAFA) (English translation: *Danish Academy of Science Education* - For a short English introduction see the homepage: About NAFA - NAFA). NAFA is a national program supported by Novo Nordisk Fonden and VILLUM FONDEN with more than 25 million Euros in the period from 1st August 2021 to summer 2028. The main objective of NAFA is to enhance knowledge sharing and knowledge creation among science teaching professionals at different educational levels, both teacher education and primary and lower secondary schools. A central part of this is the organising of local and national PLCs at all the six university colleges in Denmark. In NAFA, a PLC is defined *as a committed and systematic inquiring community between a group of educators, who share experiences and knowledge from practice through inquiry and reflective dialogues focused on students' learning.* We will use NAFA as a case to analyse and discuss the following two research questions:

How is it possible to organize professional learning communities for science teacher educators?

How do science teacher educators experience their participation in such professional learning communities?

Method

Theoretically we build on a practice theoretical approach and a Routine Dynamics lens (Feldman, 2021; Kiær & Albrechtsen, 2024) to understand, how the science teacher educators in NAFA enact the new organizational routines in the form of 'PLC-routines' (Spillane et al., 2016). PLC-routines have a function as 'coupling mechanisms' (Spillane et al., 2011) in and between university colleges and are routines meant to support the professional learning of the science teacher educators (Horn & Little, 2010)

We explore how the idea and the actual performance of the PLC-routines constitute each other, and how different artifacts play a role in this creation of routines, using the analytic framework of Feldman & Pentland (2003). The empirical material in this paper stems from an ongoing ethnographic study that began in 2023 where we follow and observe the enactment of the PLC-routines at both online and physical meetings among the science teacher educators. Currently we have collected 61 hours audio- and video-recordings, and we have 2318 pages of transcribed data, including fieldnotes. We have also interviewed some of the science teacher educators (N=7) asking them about their experiences of participating in the PLCs of NAFA. In our paper presentation we will analyse and discuss these observations and interviews to understand how the PLCs – as defined in NAFA – are enacted in practice as new organizational routines.

Preliminary Findings

Our preliminary findings show how there is an ongoing process of building the new PLC-routines where there are examples of science teacher educators trying to find balance between the ostensive and performative aspects of the PLC-routines. The Routine Dynamics perspective enables us to describe and understand these processes in depth. We see a potential in using this approach for further investigation of the organization of professional learning opportunities for science teacher educators (see also Wolthuis et al., 2022). Our analysis of the empirical material from our observations and interviews also show how different artifacts are used to organise the PLCs and establish the new routines such as the use of a Teams platform with different folders, inspirational materials, collaboration agreements, theme reports, meeting agendas etc. The

interviewed science teacher educators explain how they work together, when and how often they meet, facilitate the meetings, invite experts to the meetings, include pre-service and in-service students in their activities, plan instruction, make decisions and communicate with science teacher educators from other university colleges. The PLC meetings we have observed are quite different in how they are enacted although they all work with the same overall theme (such as technological literacy) and we also see how the part of doing inquiries together seems limited. In the paper presentation we will discuss the possible implications of the findings for the further development of PLC-routines for science teacher educators.

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Fostering STEM Teacher Identity Development In Primary And Secondary Science Education

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Integrated STEM (Science, Technology, Engineering, and Mathematics) education is promoted as an approach that equips students to address complex real-world challenges. Its implementation, however, requires teachers to move beyond single-subject instruction and adopt interdisciplinary roles and practices. This study examines the development of STEM teacher identity among primary and secondary science teachers participating in a 7-month professional development programme. Guided by the Dynamic Systems Model of Role Identity (DSMRI), the research explores shifts in teachers' self-perceptions, beliefs, goals, and perceived action possibilities. Twenty-four in-service teachers engaged in collaborative curriculum design, reflective activities, and classroom implementation of STEM modules, supported by mentors within learning communities. Data were collected through questionnaires, reflective journals, and recordings of community meetings. Findings revealed differentiated trajectories of professional identity development. Many teachers, particularly at the secondary level, underwent transformational change, marked by expanded perceived action possibilities, more integrated epistemic understandings of STEM, and greater use of design-oriented, inquiry-driven practices. Others followed a more elaborative trajectory, extending existing practices with interdisciplinary elements while retaining aspects of prior disciplinary orientations. Across both groups, self-perceptions remained comparatively stable, suggesting that changes in professional self-understanding may require more sustained identity-focused support.

Keywords: STEM education, Teacher education

Introduction

Contemporary global challenges are increasingly understood as complex, wicked problems characterized by the interaction of environmental, technological, and social factors. Addressing such challenges in educational settings requires interdisciplinary teaching approaches that highlight the critical links between distinct disciplines and provide opportunities for students to apply knowledge and relevant skills to complex problem situations in ways that mirror the interconnected nature of scientific, technological, and societal decision-making (Schpakow & Zambak, 2025).

The integrated STEM (Science, Technology, Engineering, and Mathematics) approach operationalizes this interdisciplinarity in classroom practice. Integrated STEM denotes instructional designs that deliberately interconnect disciplinary and interdisciplinary knowledge and practices around authentic, real-world problems (Kelley & Knowles, 2016). Despite variation across frameworks, descriptions of integrated STEM tend to converge on a set of core pedagogical principles, emphasizing learning through inquiry and problem-based processes, engaging students in authentic STEM practices, and positioning engineering design as a central organizing structure for instruction (Johnson & Czerniak, 2023; Roehrig et al., 2021). When coherently enacted, integrated STEM enables students to apply interdisciplinary knowledge across contexts and supports competencies necessary for addressing complex challenges such as systems thinking, problem framing, and evidence-informed decision making.

Implementing integrated STEM requires teachers to move beyond subject-matter knowledge. This, in turn, calls for targeted professional development that supports pedagogical design, collaboration, and work with open-ended problems. In this study we position teacher identity as

the principal analytic lens for understanding professional development (Avraamidou, 2014). Compared with purely knowledge-centred or competence frameworks, an identity lens is more inclusive; it encompasses teachers' beliefs, self-perceptions, and motivations, thereby acknowledging the personal and professional meanings teachers attach to instructional change (Russ, et al., 2016). Although there is no universally accepted definition of what teaching identity consists of, the literature consistently portrays it as encompassing the ways teachers understand and position themselves in relation to teaching, learning, and subject matter, while also being shaped by how they are recognized by others within their professional contexts (Avraamidou, 2014). Rather than a fixed personal attribute, teaching identity is understood as a dynamic and evolving construct that develops over time through experience. It comprises multiple, interacting sub-identities formed through engagement with diverse social, institutional, and disciplinary contexts, and it plays a significant role in shaping teachers' instructional choices (Beauchamp & Thomas, 2011; Capps, Crawford, & Constas, 2012).

From the perspective of identity, in order for teachers to effectively implement the integrated STEM teaching approach they must develop a strong STEM teacher identity; that is, a professional stance that goes beyond teaching subjects in isolation and instead embraces the integration of knowledge, practices, and purposes across disciplinary boundaries (El Nagdi et al., 2018). A teacher with a strong integrated-STEM identity is characterized by a coherent professional self-image as an educator who works across STEM disciplines and is recognized as such within their professional community. This identity is further reflected in strong self-efficacy for designing and implementing inquiry-driven STEM learning experiences, as well as in a redefinition of their role from content delivery toward the facilitation of student-centred problem solving. Moreover, teachers who enact such an identity demonstrate a willingness to experiment, tolerate ambiguity in their instructional practice, and engage in sustained collaboration with colleagues across grades and disciplinary boundaries, practices that are essential in interdisciplinary and design-oriented learning environments (El Nagdi et al., 2018, Galanti & Holincheck, 2022).

A tool that in this study helped us operationalize this complex identity construct is the Dynamic Systems Model of Role Identity (DSMRI; Garner & Kaplan, 2019). The model starts from a socio-cultural view of learning emphasizing the importance of the particular social and educational context in shaping teachers' identity. DSMRI conceptualizes identity as a dynamic system composed of five interacting components: (i) teachers' ontological and epistemological beliefs - in other words, assumptions about knowledge and learning; (ii) purposes and goals teachers set for their instruction; (iii) self-perceptions and role definitions - including perceived competence and self-image; (iv) perceived action possibilities - the behaviours and strategies teachers consider feasible in their context and (v) action which represents the enactment of identity in practice. In this context, STEM education professional development will manifest itself in the enrichment of STEM teacher identity components with new elements, as teachers encounter new practices, expectations, and forms of collaboration. Depending on the number and strength of these changes, shifts in identity are characterized as transformation, elaboration or stagnation (Gunersel et al., 2016).

Building on the conceptualization of teacher identity as a dynamic construct, this study aims to explore how primary and secondary science teachers develop a STEM teacher identity while participating in a professional development program focused on climate-change education. In particular, we examine how this development is reflected across the components of the DSMRI model and how identity tensions emerge, are negotiated, and potentially mediate or constrain these processes of change.

To address this aim, the study is guided by the following central research question:

What shifts occur in the ways teachers manifest aspects of STEM teacher identity during the aforementioned professional development program?

Methodology

Research Context And Design

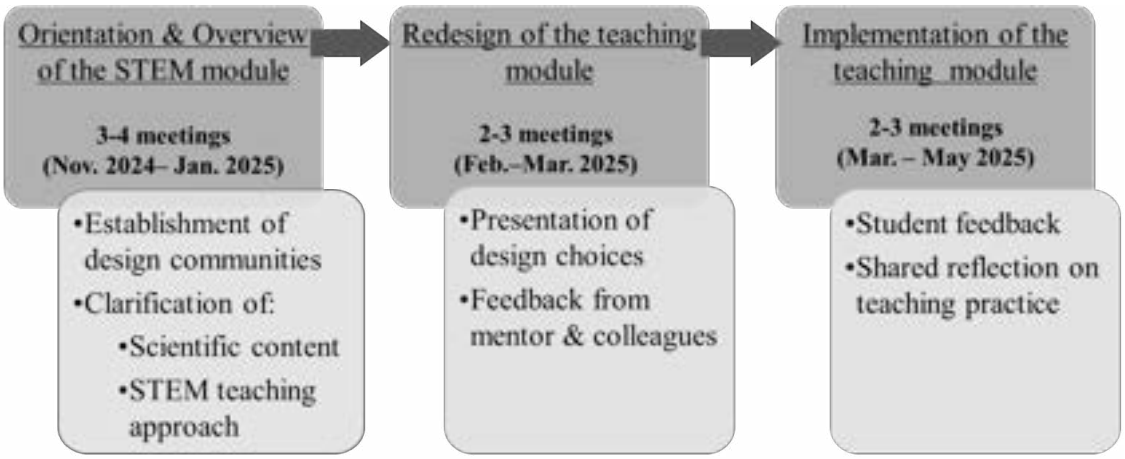
This study was conducted within the STEM-id project (https://stem-id.edc.uoc.gr/en/) aimed at supporting teachers in integrating STEM approaches with climate-change content into coherent classroom lessons across educational levels. The project was structured in two interrelated phases that combined material development with teacher professional learning.

In Phase A, eight mentor teachers engaged in a community of practice with STEM education and climate science researchers. Within this collaborative setting, they were introduced to key principles of integrated STEM and climate change education and jointly developed an integrated STEM teaching module on climate change. The teaching module was deliberately designed as a flexible, educative resource. Its modular structure allowed teachers to select, reorder, combine, or omit activities according to their classroom context. It also included prompts for adaptation, optional extensions, and differentiation strategies across grade levels.

Building on this groundwork, Phase B — which constituted the context of this study — engaged twenty-four teachers (twelve primary and twelve secondary) in a structured professional development program focused on STEM teacher identity. The program was centred on the module developed in Phase A and supported by the mentors within design communities. Participating teachers varied in teaching experience (between 3 and 18 years) and none had prior formal training in climate education or integrated STEM approach.

The professional development program lasted approximately seven months and was organized around a series of synchronous community meetings complemented by asynchronous design and reflection activities. Training occurred within designing communities, where the teachers worked collaboratively and received ongoing support from the eight mentors. An overview of this sequence of collaborative activities - from initial orientation, through redesign of teaching materials, to classroom implementation and reflection - is presented in Figure 1.

Figure 1. Phased structure of the professional development programme.



More specifically, the program began with group meetings aimed at clarifying key scientific concepts, introducing the integrated STEM approach, and familiarizing teachers with the module. Teachers then selected activities, designed and synthesized their own lesson plans, received

feedback from mentors and peers, and subsequently implemented those plans in their classrooms, allowing them to iteratively connect design decisions with classroom realities.

Data Collection

To capture teachers' perspectives and evolving understandings throughout this process, multiple qualitative data sources were collected. Primary data included teachers' open-ended initial questionnaires and the reflective journals they kept throughout the professional development process. The initial questionnaires elicited teachers' prior experiences, beliefs, and expectations regarding STEM and climate-change teaching, thereby providing a baseline for identity-related analysis. The reflective journals captured teachers' ongoing sense-making, challenges, and evolving perceptions of their role during the design and implementation phases. In addition, learning community meetings were audio-recorded, capturing discussions and feedback among mentors and teachers, as well as moments of negotiation, uncertainty, and emerging shared understandings.

All participants provided informed consent for their participation and for the recording of meetings, and all data were anonymized prior to analysis.

Data Analysis

Table 1. Coding scheme identifying manifestations of DSMRI identity components.

DSMRI Components	Subcategories
Ontological & Epistemological beliefs	Statements expressing knowledge & beliefs about: - Scientific content of Climate change - S-T-E-M disciplines connections - STEM teaching approach - Students
Self-perceptions	Statements on: - Teaching role (facilitator/mentor) - Self-efficacy for STEM teaching
Purpose & Goals	Statements expressing teaching objectives: - Learning scientific content - Solving real-world problems - Applying knowledge - Environmental awareness - Sustainability values
Perceived action possibilities	Statements expressing: - implementation of experimental activities - engineering design activities - use of ICT

For data analysis we used qualitative content analysis methods with an abductive coding strategy, combining theory-driven and data-driven codes to iteratively refine categories (Bryman, 2016). For coding we used DSMRI components and related subcategories. These categories captured

teachers' oral or written statements about ontological and epistemological beliefs, self-perceptions, purposes and goals, and perceived action possibilities, as summarized in Table 1.

To examine identity development over time, we characterized the level of change in each DSMRI component as radical, moderate, or no change, following an adaptation from Gunersel et al. (2016). Radical change denotes a component that was initially limited or absent and later became extensively developed; moderate change denotes an initially developed component that became more elaborated; no change denotes no meaningful difference across time, based on comparisons between early and later data sources for each teacher.

Combining these component-level judgments produced an overall profile for each teacher that reflects the pattern and intensity of change across DSMRI components. These profiles, summarized in Table 2, enabled cross-case comparison while preserving attention to individual developmental trajectories.

Table 2. Criteria used to characterise the overall pattern of identity change.

Identity change	Description
Transformation	At least 4 radical change occurs in a DSMRI component
Elaboration	At least 4 moderate changes occur in DSMRI components
Stagnation	No change or fewer than 4 moderate changes occur in DSMRI components

Results

Changes in STEM Teacher Identity Components

Table 3. Distribution of primary and secondary teachers by level of change across DSMRI identity components.

Identity components	Radical change		Moderate change		No Change	
	Prim	Sec	Prim	Sec	Pri	Sec
Ontological & Epistemological beliefs	5	2	6	4	4	3
	Total: **7**		*Total:* **10**		*Total:* **7**	
Purpose & goals	2	4	8	6	2	2
	Total: **6**		*Total:* **14**		*Total:* **4**	
Perceived action possibilities	4	8	5	2	3	2
	Total: ***12***		*Total: 7*		*Total:* **5**	
Self-perceptions	2	2	5	3	5	7
	Total: **4**		*Total:* **8**		*Total:* **12**	

This section presents the findings concerning changes in teachers' STEM teacher identity as they participated in the professional development program. Guided by the DSMRI framework, the analysis focuses on how different components of role identity were manifested and reconfigured over time.

Table 3 presents the distribution of teachers who manifested shifts in STEM teacher identity across the DSMRI components. Each component shows a different degree of change, reflecting both teachers' initial identity configurations and the extent of reorientation required to engage with the integrated STEM approach.

Examination of these distributions reveals three notable patterns. First, the largest number of radical changes occurred in perceived action possibilities - twelve teachers in total - and these radical shifts were concentrated among secondary teachers (eight of twelve). This pattern suggests that many secondary teachers reconsidered what forms of classroom activity they viewed as feasible, moving toward more complex and design-oriented STEM practices. For example, a secondary teacher moved from a constrained, low-effort plan (just to show a video) to a concrete classroom enactment involving student data collection and iterative testing. In the initial questionnaire she stated:

> As I teach in a high school and class time is very limited, I have not taught anything related [to climate change] before. I would probably show a video to give them some food for thought.

In contrast, during the redesign phase she wrote in her reflection journal:

> For the climate change solutions, students will build a system to measure real-time CO_2 emissions so they can test the effectiveness of their constructions.

In DSMRI terms, this illustrates an expansion of perceived action possibilities, as the teacher envisioned and intended hands-on, authentic STEM tasks that students can carry out within class time, rather than only passive exposure. At the same time, this shift in lesson planning implies a redefinition of her instructional role, from content deliverer toward facilitator of student-centred inquiry, a transition that aligns closely with the identity of an integrated-STEM teacher.

A second pattern concerns shifts in ontological and epistemological beliefs, observed in seven teachers, the majority of whom were primary educators, suggesting a reorientation in how they conceive what STEM teaching is for and how knowledge is produced in those lessons. For example, one teacher initially defined STEM as "all about the educational robotics competitions the kids take part in". After collaborative design meetings he reframed STEM as:

> It's not enough to know Math, Physics, etc; you must support students in their constructions within the engineering design cycle so they can apply what they know.

This contrast points to a shift from associating STEM primarily with discrete activities toward viewing it as a learning process that involves guided design and the application of knowledge.

In addition to these more pronounced transformations, numerous teachers exhibited moderate shifts in their instructional purposes and related beliefs. These changes often took the form of extending existing goals - such as content understanding - to include broader aims related to problem solving, real-world relevance, or environmental awareness, while still retaining elements of their prior instructional orientation.

By contrast, self-perceptions emerged as the most stable DSMRI component, with twelve cases showing no change, and secondary teachers particularly reporting stable, high STEM teaching self-efficacy. This relative stability may reflect the resilience of self-evaluative beliefs, which are

often less susceptible to short-term change, or a tendency toward optimistic self-assessment in self-reported data.

Patterns Of STEM Teacher Identity Change

When considering the aggregated patterns of identity change across DSMRI components, most identity shifts were classified as Transformation, with secondary teachers comprising the larger share of those transformations - consistent with the concentration of radical changes we saw in action possibilities and epistemic framing.

Table 4. Overall patterns of STEM teacher identity change among participating teachers.

Types of identity change	Primary	Secondary	Total
Transformation	5	8	13
Elaboration	6	3	9
Stagnation	1	1	2

Primary teachers more often followed an Elaboration trajectory, which may be associated with their prior use of cross-domain and project-based practices that could be extended rather than fundamentally replaced. In contrast, secondary teachers - often working within more rigid disciplinary structures and curriculum constraints - appeared to undergo more visible reconfigurations of their instructional repertoires, resulting in Transformation profiles.

Finally, two teachers showed no detectable change across components. These cases point to the importance of examining contextual constraints, such as workload or school-level support, as well as strongly held prior beliefs that may limit engagement with identity-related change processes.

Discussion

The findings of this study point to two distinct trajectories of teacher identity development within the professional development context. In the *Transformation* profile, teachers deepened their science knowledge, gained confidence with engineering, and adopted interdisciplinary STEM conceptions. Moreover, they reframed their instructional goals from knowledge acquisition toward skills development such as systems thinking and problem solving (Eilam, 2022), and introduced experiential and engineering, design-based activities for climate problems - a move consistent with calls to foreground engineering design as a central organizing practice in integrated STEM (Stohlmann et al., 2012). These shifts suggest a reconfiguration not only of classroom practices but also of the underlying purposes and epistemic orientations that frame teaching and can enable more coherent forms of integrated practice (Ennes et al., 2021).

By contrast, teachers classified under the *Elaboration* profile demonstrated more incremental forms of change, where mostly moderate and a few radical changes were concentrated in teachers' perceived action possibilities and in purposes and goals, while beliefs often retained disciplinary anchors that were enriched with interdisciplinary elements. In these cases, teachers expanded their instructional goals toward application and problem solving yet frequently continued to rely on established knowledge-centred routines. Such a pattern aligns with research describing additive pathways to integrated STEM, in which teachers integrate new practices into existing professional identities rather than fundamentally replacing them (Guzey et al., 2016). From an

identity perspective, this trajectory may reflect a process of negotiation, where elements of integrated STEM are accommodated within pre-existing frameworks of meaning and practice.

Across both profiles, self-perceptions appeared comparatively stable, as only a few teachers revised how they saw their role as STEM educators. The relative persistence of this component is consistent with literature suggesting that shifts in self-perception often require more explicit and sustained identity work than changes in practices or goals alone (Rushton et al., 2023).

Conclusions

Overall, this study contributes to a growing body of research that conceptualizes teacher change in integrated STEM education not merely as the adoption of new practices, but as a dynamic process of identity development shaped by the interaction between beliefs, goals, perceived possibilities for action, and professional self-perception.

In conclusion, the findings of this study suggest three interrelated implications for teacher practice and the design of professional development in integrated STEM education. First, when teachers reconceptualize STEM learning from a focus on disciplinary content toward processes and transferable skills, corresponding shifts tend to occur in classroom practice, including greater use of engineering design tasks and iterative forms of inquiry. The enactment of such practices, particularly when they were experienced as feasible and pedagogically valuable, appears to reinforce and further reshape teachers' epistemic beliefs and instructional goals, suggesting a mutually reinforcing relationship between changes in practice and teachers' developing professional identities.

Second, shifts in teachers' self-perceptions as STEM educators seem to require more targeted and explicit forms of support, such as structured reflective activities, opportunities for social recognition within professional communities, and sustained mentoring relationships.

Finally, the identification of multiple identity development trajectories highlights the need for professional development models that combine short-term support for instructional redesign with longer-term processes of identity work. Such models should be responsive to teachers' starting points, acknowledging that primary and secondary teachers may differ in their prior experiences with interdisciplinary practice, curricular flexibility, and disciplinary identification.

Ultimately, supporting teachers in adopting integrated STEM approaches requires recognizing professional learning as an ongoing process of identity development, in which changes in practice, beliefs, and self-perceptions evolve in mutually reinforcing ways over time. Future research may further illuminate how these identity trajectories are sustained across longer time scales and varied educational contexts.

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Didactic Dimension Of The Professional Identity Of Tunisian Physics And Chemistry Teachers

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This research explores determinants of teachers' action and the didactic dimension of professional identity in physics and chemistry teaching. Drawing on the Joint Action Theory in Didactics (Sensevy & Mercier, 2007; Sensevy, 2011), we analyse in situ classroom practices to characterise this didactic dimension. Our analytical approach combines a pragmatic analysis of teaching activity with a didactic perspective on knowledge construction. The study is based on six qualitative case studies involving Tunisian secondary school teachers, combining classroom video recordings, interviews, and curriculum analysis, with students aged 15 to 19. Results reveal recurrent instructional configurations across cases: teacher-controlled knowledge progression structured by Initiation–Response–Evaluation interactions, student activity mainly oriented towards participation, strong reliance on curricular resources, and an empirico-inductive practical epistemology.

These shared configurations are interpreted both as determinants of instructional action and as indicators of the didactic dimension of professional identity. This dimension is characterised through recurrent ways of organising knowledge, student activity, and instructional progression. The study suggests that this didactic dimension is not only constructed through classroom practices, but also contributes to orienting teachers' instructional choices, in relation with practical epistemology and joint didactic action.

Keywords: Professional identity; Joint Action Theory; Science teaching

Introduction

Research in science education has consistently shown that students' attitudes towards science—particularly physics—tend to decline during secondary schooling, affecting motivation, engagement, and learning outcomes (Osborne et al., 2003; Adesoji, 2008). These attitudes are considered a central component of scientific literacy and are closely related to students' beliefs about science and their perceived competence (OECD, 2007). Among the factors influencing these attitudes, teaching practices play a decisive role (Gauthier et al., 2005; Blazar & Kraft, 2017). Understanding how teachers organise classroom activity and introduce disciplinary knowledge therefore constitutes a major research issue.

In parallel, research on teachers' professional identity has highlighted its dynamic and situated character, constructed through practice and shaped within institutional frameworks (Dubar, 1994; Cattonar, 2001; Lasky, 2005). Professional identity both guides classroom action and is reshaped by it. In science education, several studies have underlined the influence of disciplinary epistemologies on teaching practices, particularly in physics and chemistry (Robert & Robine, 1989; Boilevin, 2013). However, relatively little attention has been paid to the didactic dimension of professional identity—that is, the way teachers relate to disciplinary knowledge and organise its transmission in classroom interactions.

The present study addresses this gap by focusing on Tunisian secondary school physics and chemistry teachers. We adopt the Joint Action Theory in Didactics (JATD; Sensevy, 2012) as an analytical framework to examine classroom practices as joint actions between teachers and students organised around knowledge. This perspective allows us to move beyond descriptive accounts of teaching activity and to infer macroscopic determinants of teacher action from

recurrent instructional configurations, including practical epistemologies and institutional framing through curricula and textbooks.

Our research is based on six qualitative case studies combining classroom video recordings, interviews, and curriculum analysis. Rather than concentrating on individual teaching styles, we identify recurrent features of practice across cases in order to characterise shared determinants of instructional action and to examine how the didactic dimension of professional identity both emerges from teaching activity and contributes to structuring it.

The study addresses the following research questions:

1. How do common characteristics of classroom practices allow us to infer determinants of teacher action in physics and chemistry teaching?
2. How do these determinants contribute to the didactic dimension of teachers' professional identity, and in what ways does this dimension act as a structuring principle of instructional action?

By articulating classroom practices with professional identity through a didactic lens, this study aims to clarify how stabilised ways of relating to knowledge and student activity organise teaching in physics and chemistry classrooms.

Theoretical Framework

Professional Teaching Identity And Its Didactic Dimension

Over the past two decades, professional identity has emerged as a major focus in educational research, conceptualised as a dynamic and situated process shaped through practice and social interactions (Knowles, 1992; Connelly & Clandinin, 1999; Dubar, 1994). Professional identity enables teachers to recognise themselves as members of a profession while being recognised as such by others (Cattonar, 2001). It encompasses shared professional norms as well as individual trajectories, negotiated within institutional and contextual constraints.

From this perspective, identity is not understood as a fixed attribute but as continuously constructed through teaching activity. It both guides classroom action and is reshaped by it (Lasky, 2005). Previous studies in subject-specific didactics have shown that disciplinary knowledge plays a central role in this construction, influencing how teachers interpret curricular prescriptions and organise learning situations (Robert & Robine, 1989; Boilevin, 2013).

In this study, we focus on the *didactic dimension* of professional identity, defined as the way teachers conceive disciplinary knowledge and organise its transmission in classroom interactions. This dimension includes teachers' epistemological orientations, their positioning in relation to knowledge, and the instructional strategies through which scientific content is made accessible to students. Rather than approaching identity through declared beliefs, we examine it through recurrent classroom practices, considering these practices as observable manifestations of underlying professional dispositions.

Joint Action Theory In Didactics

To analyse classroom practices, we adopt the Joint Action Theory in Didactics (JATD; Sensevy & Mercier, 2007; Sensevy, 2011), which conceptualises teaching and learning as a joint action between teachers and students organised around knowledge. Within this framework, didactic activity is understood as the functioning of a system composed of three interdependent components: teacher, students, and knowledge.

JATD provides conceptual tools for analysing how knowledge emerges and evolves during classroom interactions. Central among these are the notions of didactic contract and didactic

milieu (Brousseau, 1980). The didactic contract refers to the implicit expectations governing teacher–student interactions, while the milieu designates the set of material and symbolic resources that support learning activity. Changes in one necessarily imply adjustments in the other.

Didactic action is further characterised through the processes of mesogenesis (construction of knowledge objects), chronogenesis (temporal organisation of learning), and topogenesis (distribution of epistemic responsibility between teacher and students) (Sensevy, 2012). These concepts allow us to analyse how teachers structure classroom activity and position students with respect to knowledge.

In JATD, classroom activity can be modelled as a succession of learning games, during which teachers and students jointly engage with specific knowledge stakes. Learning is understood as the progressive acquisition of epistemic capacities through participation in these games.

Methodology

This study adopts a qualitative multiple case study design focusing on six secondary school physics and chemistry teachers in Tunisia. The teachers were selected to reflect variability in teaching experience, grade levels, and school contexts. Their classes involved students aged between 15 and 19 years.

Data Collection

Data were collected through a combination of classroom video recordings, teacher interviews, and document analysis. For each case, full teaching sessions were filmed, covering both theoretical lessons and practical activities. These recordings constituted the primary empirical corpus.

In addition, pre- and post-lesson interviews were conducted with each teacher in order to clarify instructional intentions and refine the interpretation of classroom interactions. Official curriculum documents and textbooks were also analysed to account for institutional framing of teaching practices.

Analytical Approach

Following a clinical approach of ordinary classrooms, the analysis aimed to identify recurrent features of practice rather than individual teaching styles. Video data were fully transcribed and organised using Transana software, allowing segmentation of classroom interactions into instructional sequences and interaction patterns.

The analytical process proceeded in four stages. First, each lesson was examined to characterise dominant modes of interaction and task structures. Second, practices were compared across cases to identify recurring patterns. Third, these patterns were interpreted in terms of didactic strategies and practical epistemologies. Finally, we inferred macroscopic determinants of teacher action—such as epistemological orientations and institutional constraints—and examined how these determinants contribute to the didactic dimension of professional identity.

In line with the Joint Action Theory in Didactics, particular attention was paid to the distribution of epistemic responsibility between teachers and students, the nature of tasks proposed, and the ways scientific knowledge was introduced and stabilised during classroom activity.

Rather than relying on teachers' declared beliefs alone, this methodology prioritises observable classroom practices as empirical indicators of professional dispositions. By triangulating video data, interviews, and curriculum materials, the study seeks to establish robust links between recurrent instructional practices and shared components of professional identity.

Results

Analysis of the six classroom case studies reveals recurrent patterns of instructional practice across physics and chemistry lessons. These patterns concern classroom discourse, the nature of student tasks, and the way scientific knowledge is constructed. Rather than isolated teaching styles, they point to shared modes of organising teaching and learning.

Teacher-Controlled Knowledge Progression: Dominance Of The IRE Pattern

Across all six cases, classroom interactions predominantly followed an Initiation–Response–Evaluation (IRE) structure (Sinclair & Coulthard, 1992). Teachers initiated exchanges through closed questions, students provided brief responses, and teachers evaluated or reformulated these answers before moving on.

In this dialogic lecture format, the progression of knowledge remained largely under teacher control. Students' contributions were mainly limited to completing expected statements or recalling previously introduced information. For example, during a chemistry lesson on acid–base titration, the teacher guided students step by step towards the expected formula, leaving little space for alternative reasoning or conceptual elaboration.

Excerpt 1 (P6, titration lesson). The interaction follows an IRE pattern in which knowledge progression is tightly controlled by the teacher

T: We performed a titration… for example… you titrated an acid with a base. What exactly are we determining when we titrate the acid? (1:32:51)

Class: …

T: At equivalence, what do we have? (1:32:55)

Class: …

T: What relation do we have? (1:33:00)

S: The number of moles. (1:33:04)

T: Yes… yes, yes. What do we have then? (1:33:10)

Class: …

T: Earlier… what did we say? (1:33:17)

Class: …

T: At equivalence, we have… as a relation… if it's a monobasic acid and a monobasic base. (1:33:24)

Class: …

T: So we say CAVA equals… (1:33:27)

Class: CbVb

T: CAVA equals CbVb. Then, from this relation, what are we going to determine? (1:33:35)

S: The number of moles of acid.

This interactional pattern ensured curriculum coverage but restricted opportunities for students to engage in deeper conceptual discussions. In this configuration, epistemic responsibility remained largely on the teacher's side, with students positioned primarily as respondents rather than as contributors to knowledge construction.

Low Epistemic Demand Of Student Tasks

A second recurrent feature concerns the nature of tasks proposed to students. In both physics and chemistry lessons, activities mainly involved reproducing experimental protocols already designed by the teacher or described in textbooks. Students carried out basic measurements

(volume, mass), mixed reagents, or observed predefined phenomena, but rarely participated in designing experiments or formulating investigative questions.

Although students were kept active through frequent questioning and hands-on manipulation, their engagement remained largely procedural. Tasks required execution rather than interpretation, and conceptual demands were limited. As a result, student activity was equated with participation, without necessarily involving knowledge construction. This procedural orientation is illustrated in Excerpt 2.

Excerpt 2 (P1, practical work). Student action is largely constrained to reproducing a protocol already prepared by the teacher

T: This is [T points with finger] sodium bicarbonate.

Scheima: Should I put it all?

T: Just a small amount.

T: Bilel, add a few drops of the sulfuric acid solution. [Bilel picks a test tube at random, the teacher intervenes] No, no, a flask [an Erlenmeyer]. You need to read the labels.

Classroom observations showed that students followed step-by-step instructions with little opportunity to modify procedures or explore alternative explanations. This organisation supported technical familiarity with laboratory practices but offered few occasions to engage with scientific inquiry as a process of hypothesis generation and testing. Overall, student engagement was high in terms of participation, yet its epistemic value remained low: being active does not necessarily mean building knowledge.

Empirico-Inductive Construction Of School Science

Across cases, scientific knowledge was systematically introduced through observation-based situations drawn from experiments, textbook activities, or videos. Lessons typically began with concrete phenomena, such as chemical reactions (e.g., zinc and copper sulfate), stoichiometric transformations illustrated by indicator colour change, inertia observed through space-probe videos, wave propagation via elastic-string vibration, concentration through tasting sugar solutions, or acids–bases through everyday examples (heartburn and antacids).

These activities were followed by teacher-led generalisations, during which scientific relations or definitions were formalised. Students were expected to move from observation to accepted conclusions, without being invited to formulate hypotheses, explore alternative explanations, or engage in theoretical modelling. Across the six classrooms, opportunities for questioning results, comparing interpretations, or examining underlying assumptions remained limited. As a consequence, scientific knowledge was presented primarily as a set of established facts derived from empirical observation rather than as a process involving uncertainty, argumentation, and conceptual construction.

Taken together, these recurrent instructional configurations point to an empirico-inductive epistemology in which knowledge appears to emerge directly from observable phenomena and experimentation. Within this framework, science is framed as stable and authoritative, constraining students' engagement with scientific reasoning as a dynamic and dialogical practice.

Recurrent Classroom Practices

Taken together, the six case studies reveal four recurrent features of classroom practice:

- a dialogic lecture format structured by IRE interactions;

- teacher-driven progression of knowledge;
- student tasks characterised by low epistemic demand;
- inductive construction of school science based on experiments or textbook examples.

These shared patterns suggest common ways of organising teaching and learning in physics and chemistry classrooms, beyond individual differences between teachers.

Taken together, these recurrent classroom practices point to shared ways of organising knowledge, student activity, and instructional progression. In line with our analytical framework, we now move from the description of these practices to the identification of macroscopic determinants of teacher action, in order to examine how they contribute to the didactic dimension of professional identity.

Discussion

The results make it possible to move beyond the description of classroom practices to infer shared determinants of teacher action across the six cases. These determinants concern teachers' relationship to knowledge, their conception of student activity, the institutional framing of teaching through official curricula and textbooks, and their practical epistemology. Together, they constitute central components of the didactic dimension of professional identity.

First, teachers position themselves primarily as holders and transmitters of knowledge. This is evidenced by the dominance of IRE interactions and teacher-controlled progression of scientific content. Within the Joint Action Theory in Didactics, this configuration corresponds to a topogenesis in which epistemic responsibility remains largely on the teacher's side. Students are invited to respond but rarely to initiate or transform the knowledge at stake. Teaching is thus organised around ensuring that prescribed content is introduced and formalised, reinforcing a transmission-oriented model of instruction.

Second, student activity is consistently valued, but mainly in the sense of participation rather than inquiry. Classroom practices show that being "active" is equated with answering questions, manipulating materials, or following procedures. However, this activity carries limited epistemic weight, as tasks rarely require hypothesis formulation, interpretation, or argumentation. Student engagement therefore functions primarily as an indicator of participation rather than as a driver of knowledge construction.

Third, instructional practices are strongly structured by official curricula and textbooks. Teachers closely follow prescribed sequences and experiments, which contributes to the stabilisation of classroom routines across cases. From a didactic perspective, this institutional framing shapes both the didactic milieu and the didactic contract, orienting the organisation of tasks and the progression of knowledge.

Finally, teaching practices are underpinned by an empirico-inductive practical epistemology. Scientific knowledge is introduced through observation and experimentation and presented as a set of established relations derived from empirical evidence. Students are rarely invited to engage with theoretical modelling, alternative explanations, or the tentative character of scientific knowledge. This epistemological orientation positions science as something to be revealed through experience rather than constructed through inquiry, debate, and abstraction.

Taken together, these four determinants—teacher-centred knowledge transmission, student activity conceived primarily as participation, institutional framing through curricula and textbooks, and empirico-inductive practical epistemology—form a coherent system organising classroom action. These determinants are not interpreted here as individual teacher preferences,

but as shared professional dispositions enacted in ordinary teaching situations. Moreover, they do not only emerge from classroom practices; they also orient teachers' instructional action by stabilising recurring ways of organising knowledge and student activity. The didactic dimension of professional identity—understood as teachers' relationship to knowledge, student activity, and instructional organisation—functions as a structuring principle of teaching. It orients teachers' choices, stabilises recurring instructional configurations, and guides the way scientific content is introduced and formalised

In this sense, professional identity appears not as a set of declared beliefs, but as a stabilised configuration of practices and orientations produced and reproduced through everyday didactic activity. The didactic dimension of professional identity emerges through recurrent ways of organising knowledge, positioning students, and responding to curricular constraints. These findings support the view that professional identity both guides instructional action and is continuously shaped by it.

Conclusion And Implications

This study examined the didactic dimension of professional identity among Tunisian secondary school physics and chemistry teachers through the analysis of classroom practices using the Joint Action Theory in Didactics. By focusing on recurrent features of teaching activity across six case studies, we identified four shared determinants of instructional action: teacher-centred knowledge transmission, student activity conceived primarily as participation, institutional framing through curricula and textbooks, and an empirico-inductive practical epistemology.

These determinants are inferred from recurrent instructional configurations and constitute shared components of the didactic dimension of professional identity. They structure classroom interactions and stabilise particular ways of engaging with scientific knowledge beyond individual teaching styles. Professional identity thus appears as a stabilised configuration of didactic practices enacted in ordinary teaching activity and continuously reproduced through recurrent ways of introducing knowledge, distributing epistemic responsibility, and positioning students with respect to scientific inquiry. Importantly, the didactic dimension of professional identity does not merely emerge from teaching activity; it also acts as a determinant of instructional action. Through shared orientations towards knowledge, student participation, and epistemic responsibility, teachers mobilise stabilised professional dispositions that organise classroom activity and shape the progression of scientific content. From a theoretical perspective, this study contributes to research on teacher professional identity by grounding it in observable didactic practices and by showing how macroscopic determinants of action can be inferred from classroom interactions. The JATD framework proved useful in linking instructional organisation with practical epistemologies, offering a situated account of identity construction in science teaching. The findings also have important implications for teacher education and professional development. Making these determinants explicit may support teachers in reflecting on their epistemological orientations and instructional routines. Professional learning initiatives could build on such reflexive work to foster alternative ways of engaging students in knowledge construction, particularly by strengthening inquiry-based approaches and promoting greater epistemic diversity in classroom discourse. In this perspective, teacher–researcher cooperation within design-based approaches, such as cooperative didactic engineering (Sensevy & Bloor, 2019), offers promising avenues for supporting professional evolution while remaining coherent with curricular requirements.

Several limitations must be acknowledged. The study is based on a limited number of cases within a single national context, restricting generalisability. Future research could extend this approach to comparative studies across educational systems to examine how different institutional

configurations shape the didactic dimension of professional identity. Longitudinal and intervention-based designs would also help clarify how these determinants evolve over time and how targeted professional development might support more inquiry-oriented science teaching practices. By articulating recurrent classroom practices with practical epistemologies and institutional framing, this study contributes to a didactic understanding of how professional identity is constructed—and how it structures teaching activity—in physics and chemistry classrooms.

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Part 17 / Strand 17

Science Education In Primary And Pre-Primary Learning Contexts

Co-editors: *Ange Fitzgerald & Federico Corni*

Part 17 / Strand 17 Science Education In Primary And Pre-Primary Learning Contexts

Science education from early childhood through primary school, with wide ranging foci including science pedagogies, children's learning, innovative teaching practices, teacher education, social and cultural aspects of science engagement, and family involvement.

Sub-themes:

1) Children's science engagement
2) Pedagogies for science in the early years
3) Emergent Science
4) Early childhood science instruction
5) Primary science instruction

Contents

Strand 17: Science Education In Primary And Pre-Primary Learning Contexts 1592

Beyond The Slide: Rethinking Playgrounds As Learning Spaces 1594

Measuring Motivation And Socioeconomic Status In Primary Science Learning 1601

Learning Science Through Multimodal Representations 1608

Designing Video-Tutorials As A Supporting Tool In The Experimentation Process 1614

Creativity and Programming Essentials as Skills for a Transitioning Digital World 1622

Not Produced "For The Wastebasket" – Materials In The Fops Project 1628

Exploring Science Through Screens: An Analysis Of Mobile Apps For Preschoolers 1635

Creative Sparks And Constructive Tensions: How Resistance Shapes Young Children's Collaborative Engineering Design 1645

Learning The 5Rs To Promote Citizen Science In Primary Schools 1654

"The Living Things In Our Schoolyard": Design Of A Teaching-Learning Sequence For Primary Education 1660

Bridging Classical And Modern Physics: An Integrated Astronomy Curriculum For Primary Schools 1669

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Strand 17: Science Education In Primary And Pre-Primary Learning Contexts

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Framing Early Science Learning

This chapter in the eProceedings, related to the *Science Education in Primary and Pre-Primary Learning Contexts* strand, brings into focus a formative phase in learners' engagement with science, where foundational dispositions, identities, and ways of knowing begin to take shape. Across this strand, science education is understood not simply as the acquisition of early concepts, but as a situated and relational process through which young learners come to make sense of their natural and designed world. Contemporary research increasingly positions early experiences of science education as an active and socially mediated endeavour, where children engage through questioning, observing, exploring, and refining ideas across diverse contexts.

Learning Through Participation, Design And Experience

Across the contributions in this chapter, science learning is consistently framed as participation in scientific practices rather than the passive reception of knowledge. Inquiry, experimentation, engineering design, computational thinking, and multimodal meaning-making are positioned as central approaches through which children construct understanding. Evidence continues to highlight the importance of engaging learners in meaningful science experiences from the early years, with well-designed interventions contributing to sustained learning outcomes. Importantly, these practices extend beyond the classroom. Several papers emphasise the pedagogical potential of outdoor and place-based environments, including schoolyards and green spaces, where learners engage with biodiversity, ecosystems, and environmental processes through embodied and sensory experience.

A key insight emerging across the chapter is that access to engaging or resource-rich environments does not, in itself, guarantee meaningful learning. Whether in outdoor or digital contexts, high levels of activity and participation do not necessarily lead to conceptual understanding, which highlights why the design of pedagogical environments is critical. Across the contributions, inquiry-based materials, learning–teaching sequences, and digital tools are shown to require careful structuring to support a progression from exploration to explanation. This includes balancing structure and openness to ensure that learners are supported in moving beyond interaction towards reasoning and meaning making. Within this, the role of the teacher remains central as a mediator of learning, guiding reflection and supporting conceptual development.

Agency, Coherence, And Contemporary Challenges

Young learners are consistently positioned across these contributions as capable, creative, and active participants in science learning. Creativity is framed as integral to scientific thinking, particularly within contexts such as engineering design and computational activity, while collaboration, negotiation, and even resistance, are understood as productive elements of learning. At the same time, several contributions highlight issues of equity, access, and inclusion,

drawing attention to how socioeconomic factors, access to digital resources, and the design of learning environments shape opportunities for meaningful participation.

Alongside this emphasis on participation, the strand also engages with questions of conceptual coherence and disciplinary integrity. Several papers highlight the importance of structuring learning around key scientific ideas and supporting progression towards more sophisticated understandings. This includes the design of learning–teaching sequences and the introduction of complex scientific perspectives, such as elements of contemporary physics, within primary education. Such work reflects a broader commitment to aligning early science education with the epistemological foundations of the discipline, while remaining responsive to learners' developmental trajectories.

Finally, the contributions connect strongly to broader societal priorities, particularly sustainability and digital transformation. Science education is positioned as a means of fostering awareness of human–nature interdependence and supporting engagement with environmental challenges, often grounded in local and place-based contexts. At the same time, the increasing presence of digital technologies in children's lives raises important questions about the quality and depth of learning in digital environments. While these tools offer new opportunities for engagement, their value depends on thoughtful pedagogical design and alignment with principles of effective learning.

Taken together, the papers in this chapter reflect a dynamic and evolving field that is attentive to the complexities of early science learning. They highlight the importance of designing learning environments that are pedagogically intentional, conceptually coherent, and socially responsive, while recognising young learners as capable, creative, and engaged participants in science. In doing so, the strand contributes to ongoing conversations about how primary and pre-primary science education can support more meaningful, inclusive, and future-oriented educational practices.

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Beyond The Slide: Rethinking Playgrounds As Learning Spaces

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Outdoor spaces have been shown to function as powerful pedagogical environments, enriching children's understanding of and connection with the world around them. Yet, some schoolyards remain little more than concrete jungles, devoid of natural elements and thus silencing nature's invitation to discover.

This preliminary study explores the potential of a Spanish preschool playground as a context for scientific learning. By analysing both teachers' perceptions of the playground and children's use of it, a proposal for change was developed and implemented. The findings reveal that even small modifications to the physical environment can foster changes in children's behaviour, increasing their engagement in scientific activities. Following these changes, children engaged more explicitly with scientific concepts and skills, what created opportunities to extend their interests within the classroom. These findings also highlight the central role of teachers in such spaces. Fostering meaningful science learning in free-play outdoor environments requires more than just physical transformations; it also demands that educators rethink their roles and actively support children's scientific exploration.

Keywords: Early-childhood Education, science learning, outdoor play

Introduction

Children engage with the world as if in constant dialogue with it. Driven by an innate curiosity, "they question, observe, investigate, experiment, and question again" (Raven & Wenner, 2023, p. 485). Unaware of their own scientific potential, children participate in cycles of action and reflection that help them navigate their environment and lay the foundations for their interactions with it (Pedreira & Márquez, 2019).

It is through play that this dialogue unfolds. In its spontaneous and creative nature, play provides a particularly rich context for children to explore and reflect on everyday scientific phenomena (Gomes & Fleer, 2020). This potential is especially evident in outdoor environments, where diverse sensory stimuli invite multiple forms of exploration (Speldewinde, 2024), from the crunch of leaves underfoot to the scent of flowers in bloom.

Such dynamic environments can inspire open-ended play, physical activity, risk-taking, emotional engagement, exploration, and interaction with both peers, and the environment (Speldewinde, 2024). In doing so, they become powerful allies in nurturing scientific learning. Outdoor spaces encourage children to actively engage with their surroundings, creating opportunities for meaningful, hands-on encounters with scientific ideas (Lee & Ensel Bailie, 2020). Nevertheless, despite research suggesting that it is possible to go beyond the strictly ludic in these contexts, linking playing and learning in a meaningful way (Sanz et al., 2021), the potential of play to foster scientific learning remains underexplored (Gomes & Fleer, 2020). Play is frequently positioned as separate from learning, a dichotomy that becomes even more pronounced in outdoor settings (Lee & Ensel Bailie, 2020). As a result, outdoor playtime is frequently treated as a break from formal learning rather than as a pedagogical opportunity.

In recent years, however, this trend seems to be reversing. Schoolyards are increasingly being revalued as educational spaces in which children can engage with their surroundings and learn

from them (Sanz et al., 2021). Despite this growing recognition, many schoolyards remain barren and lack natural elements (Mateo et al., 2021). Motivated by this reality, we immersed ourselves in the daily life of a Spanish preschool, analysing its schoolyard, teachers' perceptions of its educational potential and how children use it. Based on this analysis, we introduced physical modifications to the schoolyard aiming to explore how these changes influence children's physical, social, and cognitive activities, with a particular emphasis on children's scientific activities.

Study Design

The study was designed as a preliminary case study (Yin, 2014) conducted in a Spanish preschool that had initiated a process of schoolyard naturalization. The aim was to understand this preschool's needs and use these insights to design and implement playground modifications that could support children's scientific learning. To achieve this, we engaged in an in-depth immersion in the daily life of this preschool, where the first author was completing a student-teacher placement at the time.

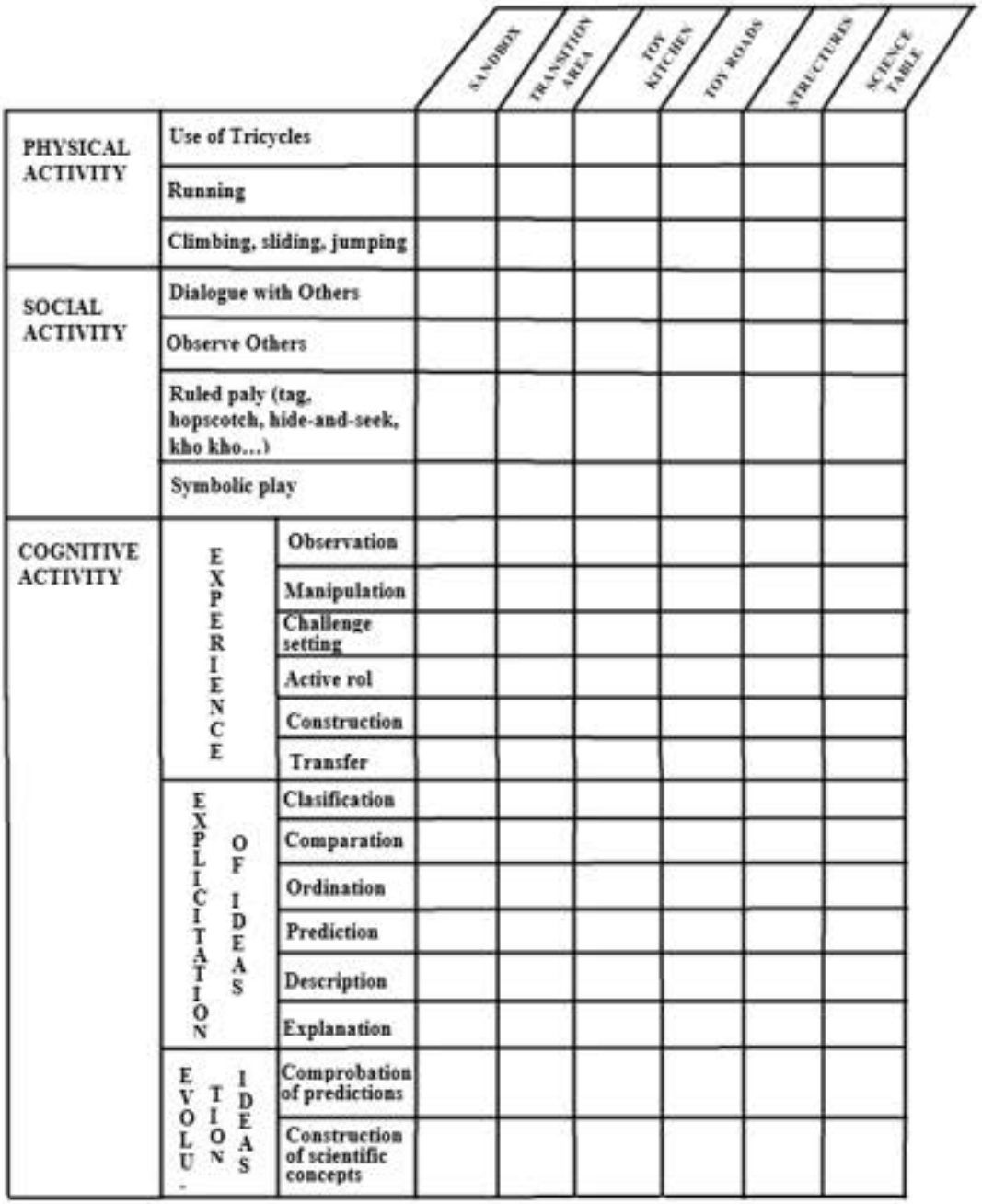
To explore the school's needs, we conducted semi-structured interviews with nine teachers. The interviews focused on teachers' perceptions of the schoolyard, including its strengths, limitations, and educational potential. Teachers were asked about their views on the space, how science learning was currently supported (or could be supported), and how the playground was used in their daily practice.

Following the interviews, we analysed how children and teachers actually used the playground. We began by identifying the different areas within it, considering the materials available and the activities that typically took place in each area to differentiate them. The areas included in the analysis are shown in the top row of Figure 1. Over a three-week period, we observed children's and teachers' behaviour during recess, the only time the playground was used. Each 30-minute recess involved approximately 170 children aged 3 to 5 years, who played freely in the playground. Given the large number of children and the size of the space, direct observation posed significant challenges. To address these, we focused on identifying recurring behavioural patterns and recorded only actions that were consistently observed across multiple days.

Data were collected through field notes and photographs. Observed activities were categorized as physical, social, or cognitive, following the example of Peinado Alamillo et al. (2022). Cognitive activities were further divided into three subcategories: experience with reality, explicitation of ideas, and evolution of ideas. These subcategories align with the three stages of the scientific activity defined by Pedreira and Márquez (2019). The observation instrument used for data collection is presented in Figure 1.

Data from all sources were triangulated to identify needs and potentialities. These findings informed the design and implementation of physical modifications to the playground. The same observation instrument was subsequently used to analyse changes in children's activities after the intervention, enabling direct comparison. The limitations of this approach are acknowledged, in line with the preliminary nature of the study.

Figure 1. Analysis template used to identify changes in children's scientific actions adapted from Pedreira and Márquez (2019) and Peinado Alamillo et al. (2022).



Findings

The interviews revealed that teachers perceive spaces as active educational agents that shape children's actions. Consequently, they emphasized ongoing collaborative efforts to transform school spaces into welcoming environments that promote learning. This perspective also extended to outdoor areas, which teachers recognized as contexts in which children learn both in and from their surroundings.

Most teachers valued recent renovations to the playground, particularly the addition of materials such as tricycles, strainers, and building blocks, which they associated with scientific learning (e.g., "*Children learn science outdoors when playing with tricycles and strainers*."). However, they also acknowledged that some areas remained underused or lacked a clear educational purpose. On this behalf, teachers expressed appreciation for our intervention in helping them reflect on the playground's potential, noting the importance of collective reflection (e.g., *"It is necessary not to have just one mind thinking, but several minds discussing."*).

When asked about their own use of the schoolyard, only one teacher reported using it outside recess. Most described adopting a non-interventionist role during break time, allowing children to interact freely with the environment. Only one teacher explicitly questioned this approach, suggesting that educators' roles in outdoor play may need to be reconsidered if the aim is to foster scientific learning.

Observational data showed that children's activities varied notably depending on the area and materials available. Overall, social, physical, and cognitively driven activities, particularly those involving direct interactions with their surroundings, were the most common (Figure 2, next page). Following the modifications, overall activity increased, with a particularly noticeable rise in cognitive engagement among children (Figure 2).

In Figure 2, blue shading indicates the activities observed in each playground area. Each cell is divided into two sections: the left side represents activities observed before the modifications, and the right side those observed afterward. The intensity of the blue tone is proportional to the number of activities observed, so that a darker tone indicates a greater number of activities. Consequently, a cell with a lighter tone on the left and a darker tone on the right shows an increase in the number of activities carried out after the modification of the playground. It is important to note that the frequency of each type of activity was not considered. An activity was considered as long as at least one child engaged in it. Post-intervention changes were analysed by comparing each activity with its occurrence prior to the modifications, without cross-area or frequency comparisons.

Activities involving the explicit articulation and evolution of ideas were the least frequently observed during recess. Although frequency was not quantitatively analysed, these interactions occurred far less often than physical activities, which were more prominent in practice despite their limited representation in the table.

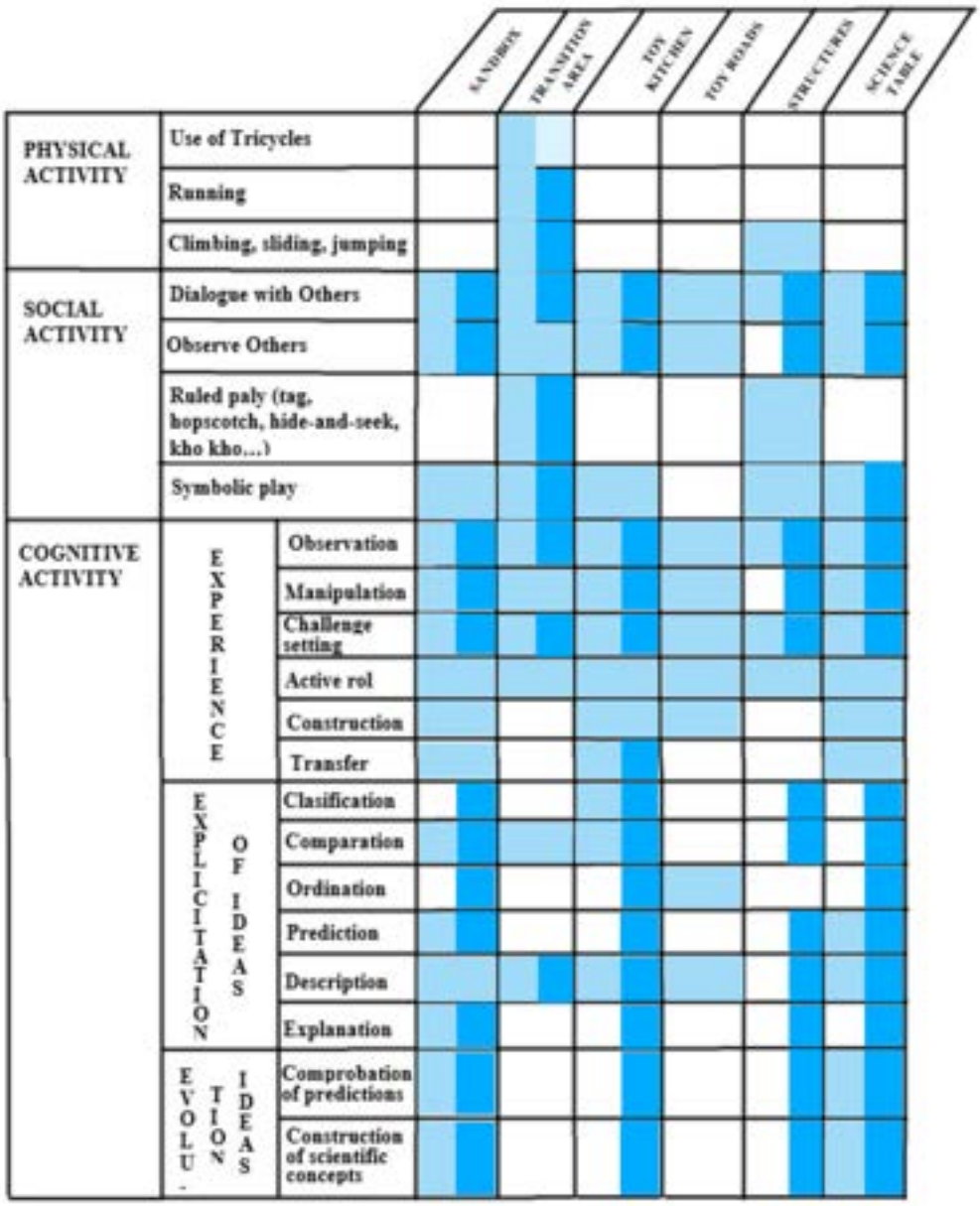
Discussion

The results of this preliminary study suggest that, although playground modifications increased overall activity and facilitated children's engagement with various scientific phenomena, physical changes alone are insufficient to ensure learning. While the modifications appeared to support children's experience with reality, activities involving explicitation and, especially, the evolution of ideas remained scarce. These latter stages are cognitively more demanding, as they require children to reflect on their experiences, make connections, and progressively transform their initial ideas. The limited presence of such activities during recess suggests that, in free-play outdoor contexts, advancing beyond direct experience towards conceptual development is unlikely to occur without intentional pedagogical support. This finding reinforces the importance of teacher scaffolding as a key element in fostering deeper forms of scientific learning, particularly when the aim is not only to provide rich experiences, but also to support meaning-making processes. In this sense, it is necessary to go beyond the design of high-quality spaces that offer meaningful experiences and accompany these experiences with pedagogical support that helps children connect evidence with scientific ideas (Gomes & Fleer, 2020; Peinado Alamillo et al., 2022).

As noted by Sanz et al. (2021), there is a tendency to over-rely on rich and stimulating environments to promote learning. In line with this observation, and echoing the reflections of one of the interviewed teachers, our findings suggest that rethinking outdoor spaces as learning environments must also involve reconsidering teachers' roles within them. The schoolyard is undoubtedly an educational space, rich in opportunities for discovery (Speldewinde, 2024).

However, recognizing its pedagogical value must go hand in hand with teaching approaches that align with this understanding.

Figure 2. Activities taking place in the different areas of the playground before (left) and after (right) the modifications.



The findings also point to the need to rethink what it means to teach and learn science in early childhood education. While some interviewed teachers emphasized the importance of strategies such as questioning or encouraging hypothesis formation, their descriptions of scientific learning in the schoolyard were often limited to references to specific activities or materials. This suggests a predominantly activity-oriented view of science learning, rather than one that considers concept formation. Such a perspective may help explain the limited teacher intervention observed during outdoor play. If scientific learning is understood simply as "*playing with specific materials,*" then further involvement may seem unnecessary. Similar patterns were identified by Gomes and Fleer (2020), who distinguish between activity-oriented and conceptually-oriented "sciencing attitude". Further research could explore teachers' attitudes towards science learning and how these perspectives shape their practices in outdoor spaces.

Figure 3. Activities taking place before and after the modifications.



In this sense, moving beyond the slide implies rethinking playgrounds not merely as spaces for physical activity or unstructured play, but as learning environments with genuine educational potential. While the design and naturalisation of outdoor spaces are important starting points, they are insufficient on their own. Fully realising the educational value of playgrounds requires teachers to adopt an active and reflective role, recognising when and how to intervene to support children's progression through the different stages of scientific activity. Only by combining thoughtfully designed environments with intentional pedagogical accompaniment can playgrounds become spaces where play and scientific learning meaningfully converge, thus enabling us to truly move beyond the slide.

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Measuring Motivation And Socioeconomic Status In Primary Science Learning

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Educational inequalities related to family income emerge early in primary school and affect children's performance and motivation in science, as well as their digital skills ('digital habitus'). To investigate the impact of digital gamification on the motivation and learning outcomes of children with different backgrounds, two child-appropriate instruments were developed and piloted: a motivation questionnaire based on the CAIMI scale (Gottfried, 1985) and a socioeconomic status (SES) questionnaire that relies solely on child-reported information. The adapted motivation scale demonstrated high reliability in the pilot study (α = .89). Although the reliability of the SES instrument is questionable (α = .55), it reflects the correct correlations with the occupational status of the parents and the social index of the respective school (a value used in Germany to describe a school's social composition).

Keywords: Inclusive Education, Socio-Economic Status, Primary Science Education

Framing Project

Within the framing project 'Level up! Digital Gamification in Primary Science Education. How Digital Gamification Affects Motivation and Learning Outcomes – Especially in Children from Families with a Lower Socio-Economic Status' (Wartig & Stinken-Rösner, 2023), we developed two questionnaires. One measures children's motivation for science, and another tries to determine children's socioeconomic status (SES) solely based on the information given by the children. Both instruments and their development are described in this article.

Context And Relevance To Science Education

In Germany, educational performance and success are significantly affected by family income (Wößmann et al., 2024). Furthermore, children from families with a lower income do not attend grammar school as often as their peers from higher-income families. Also, children from lower-income families often get lower grades even if the children's performance is the same as that of more well-to-do children (Maaz et al., 2011).

In addition, children from lower-income families have to deal with inferior motivation (Maaz et al., 2011) and often a lack of (non-)material resources to promote their interests, talents, or personal strengths (Solga & Dombrowski, 2009). As a result, by the end of primary school, less affluent children are up to two years behind their peers in STEM subjects (Schwippert et al., 2020, 2024). Such clear differences in STEM education cannot be ignored. Developing scientific literacy is essential for trusting scientific facts (Stekelenburg, 2026) and resisting misinformation (Osborne & Allchin, 2025). Therefore, it is a fundamental goal of the German school system (KMK, 2004) that is already relevant in primary education, forming the basis for further education (GDSU, 2013). In addition to the described issues, there are also disparities in the 'digital habitus' between children from lower- and higher-income families. While children from more privileged social backgrounds also use tablets or other digital devices for educational purposes, children from lower socioeconomic backgrounds mostly consume leisure content (Rudolph, 2019). This discrepancy in the utilization of digital media can lead to a further increase in inequality (Kutscher, 2019). Van Dijk (2017) describes these differences and their consequences as 'second-

level divide'. These problems contrast with the German Ministry of Education's goal of building a school where digital competencies are conveyed to everyone (KMK, 2015).

Aim And Methods

The framing project aims to determine what impact digital gamification has on the motivation and learning of students from socio-economically various backgrounds. Gamification hereby describes the introduction of gaming elements into non-gaming contexts (Kapp, 2012). Even though digital gamification shows a positive impact on intrinsic motivation (Xi & Hamari, 2019), it is barely used in primary science education in Germany (acatech & Joachim Herz Stiftung, 2023). The effects of digital gamification on lower-income children have not yet been explored.

This status quo serves as the foundation for our research question: What is the effect of digital gamification on the motivation and knowledge of students from a variety of social backgrounds in primary science education?

To address the research question, we are conducting an intervention study that includes an intervention group receiving a digital gamification treatment and a control group with approximately the same number of participants, drawn from different schools in North Rhine-Westphalia, a federal state of Germany.

A digital learning environment was designed for the intervention group, comprising several gamification components and accompanying hands-on activities for discovering different types of forces (Wartig & Stinken-Rösner, 2025). Gamification elements we used are collecting points, storytelling (Fischer & Reichmuth, 2020), and (direct) feedback (Kapp, 2012) given by a pedagogical agent (Clarebout & Heidig, 2012) or by visualizations (e.g. a wrong answer turns red, a right one turns green). We chose the direct feedback because it is a highly effective form of feedback (Kopp & Mandl, 2014). The control group explores the same types of forces with worksheets and hands-on activities, but without any kind of digital gamification.

To measure intrinsic motivation and the students' knowledge about forces in the pre- and post-test, as well as the children's SES, we needed instruments designed specifically for our target group. Intensive research showed that none of the existing instruments fit our requirements completely.

Construction Of The Motivational Instrument

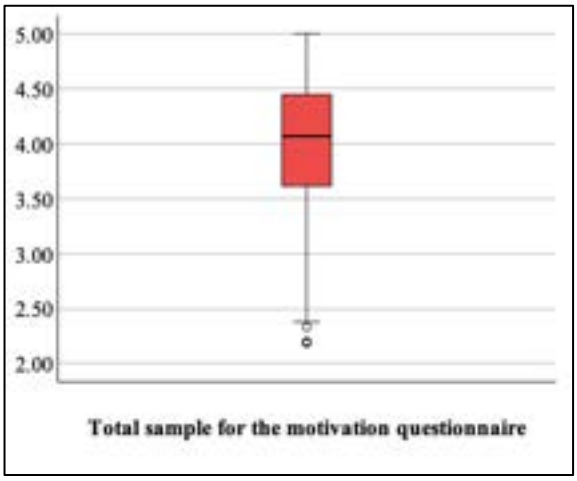
To measure the children's motivation, we developed a test based on the 'Children Academic Intrinsic Inventory' (CAIMI) by Adele Gottfried (1985). The CAIMI investigates the motivation of children between the ages of 8 and 13 in different school subjects and general academic motivation. We concentrated on the 24-items science scale, whose items are answered on a five-point Likert scale. Because the CAIMI is in English, we had to translate the science scale into German; we loosely followed the TRAPD approach (Harkness, 2003). In a first step, six different persons translated the CAIMI science scale into German. The translators stayed as close as possible to the original items. In a second step, we discussed which of the translated items best fit the original one. Hereby, language-specific terms were discussed, as it is recommended in the TRAPD approach. For example, one of the relevant issues was how to translate the word 'science'. The literal German translation (Naturwissenschaften) does not match to the name of the corresponding subject (Sachunterricht) in German primary school curricula. To prevent misunderstandings, we decided to use the term 'Sachunterricht'.

The original questionnaire includes a few negatively formulated statements (like 'I am not curious about learning things in science.'). We reformulated these into positive statements ('I am curious about learning things in science.') to reduce the impact of negative items on the answering

behaviour to a minimum (Stinken-Rösner & Laumann, 2023). Furthermore, especially younger children have problems with answering inverted questions (Woods, 2006). Since several items addressed the same thing (e.g., curiosity), but one was phrased positively and the other negatively, we ended up with duplicate items. Consequently, we deleted the duplicates. By doing so, we could reduce the questionnaire to 17 items. As provided in the TRAPD approach, we tested the modified instrument before using it in our main study (Harkness, 2003). The translated and adapted questionnaire achieved a Cronbach's $\alpha = .89$ (N = 119 fourth graders).

This result is similar to those from the original science scale, which were .69; .90; and .91 (Gottfried, 1985). Additionally, we interviewed fourth graders who did not participate in the pilot study about the questionnaire. The conversation revealed an item that the children did not understand; respectively, the children believed the item was a further duplicate. Removing the item did not affect the instrument's reliability ($\alpha = .89$, N = 119). As a result, we obtained a final questionnaire with 16 items. Furthermore, the children requested an 'I don't know' option and the option to tell the researchers their favourite primary science topic and activity. Figure 2 visualizes the results on motivation from the pilot study as a box plot.

Figure 2. The box plot illustrates the mean scores on a scale from 1 to 5, with higher values indicating a stronger level of motivation. The line within the box symbolizes the median.



Construction Of The SES Instrument

Normally, the SES of children is determined by the education, income, and occupation of the children's parents or legal guardians (Ditton & Maaz, 2011). However, this method poses the risk of a drastically reduced sample, as experience has shown that not all guardians take part in this kind of survey. The resulting challenge was to develop an instrument for the children's SES by asking only the children. For this purpose, we first analysed existing studies (for example: Andresen et al., 2020; Fishbein et al., 2024; Lenz et al., 2021; Mang et al., 2021) searching for items that give information about the SES of the participants. We categorized the items according to Bourdieu's concept of capital into the groups 'economic capital,' 'social capital,' and 'cultural capital' (Bourdieu, 1986). We identified the most frequently used items and established criteria to minimize our item pool. For example, we decided not to ask about smartphones owned by the children, because in Germany, children of primary school age often do not own a smartphone of their own for reasons other than lack of money (LFK, 2023). Additional items were developed based on recent survey results, like membership in a sports club. This question is promising because in Germany, only 40% of children from low-income families are members of a sports club, while 71% of the children from better-off backgrounds participate in sports clubs (Tempelmann et al., 2022). Furthermore, we also chose items that appear more contemporary.

All in all, we ended up with ten items. Although we know that children are not always aware of their parents' occupations (Currie et al., 1997), we included a question about it in the pilot survey. Answers were coded according to the '(Highest) International Socio-Economic Index of Occupational Status' (HISEI). The HISEI assigns numeric values to occupations based on income and educational level (Ganzeboom & Treiman, 1996; Ganzeboom, 2010) and is also used in studies like PISA (Lewalter et al., 2023).

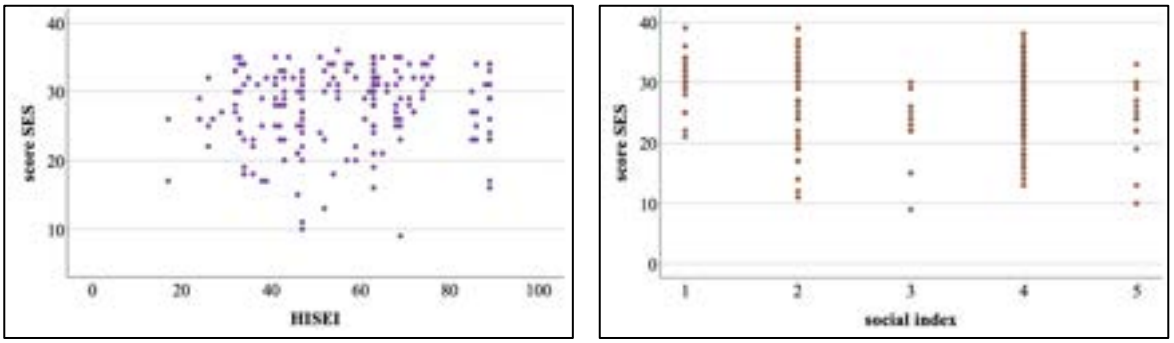
In addition, we recorded the social index of the participating schools. The social index is a value between 1 (fewer social challenges) and 9 (heavy social challenges) in North-Rhine-Westfalia (Germany) to describe the social composition of a school. The social index is based on different indicators, e.g., how many minors in the vicinity of the school receive social welfare. It can therefore be used as a rough measure of the SES of the student body, but not of individual students. Both measurements, parents' occupations and the social index of the school, are used as references to evaluate the quality of our scale.

To validate our instrument, we tested the following hypotheses:

1) The children's answers correlate positively with the parents' occupation (respectively, the corresponding HISEI).
2) The children's answers correlate negatively with the school's social index.

Piloting took place in the 'teutolab physik,' an extracurricular learning venue at Bielefeld University. After excluding one item that children constantly misunderstood, we ended up with nine final items and a questionable Cronbach's α of .55 (N = 201) for the SES-scale. However, there is a low (not significant) correlation between the SES-scale and the parents' HISEI (r = .133, p = .056; N = 207) (Figure 3, left) and a low significant negative correlation between the SES-scale and the social index of the respective schools (r = -.126, p = .032; N = 289) (Figure 3, right). For the final set of items, see Table 1 (next page).

Figure 3. Relationships Between Socioeconomic Status Indicators. *Left*: Correlation between HISEI scores and results of our SES questionnaire. *Right*: Correlation between the social index and the results of our SES questionnaire.



Discussion

The pilot study of the motivation scale shows that our questionnaire's psychometric properties are quite similar to the source questionnaire's. This indicates that our instrument can quantify the motivation of children in primary science education in Germany.

Measuring SES solely based on children's answers remains challenging. With a questionable Cronbach's α of .55, our scale does not stand out from existing instruments (cf. versions of the FAS: Corell et al., 2021; Kehoe & O'Hare, 2010). The theoretically predicted correlations between SES, parents' occupation and social index are low and only significant in the case of the social index and the SES. Even though reliability and validity are comparable to existing scales,

the strength of our questionnaire is that our items are more contemporary and much closer to the children's living environment.

Table 1. Translation of the SES items. Please note that only the German version was piloted. Items 1 and 2 are answered on a four-point Likert scale from every day to never while items 3 to 9 are yes / no questions. The last question is about the parents' / legal guardians' occupation. Moreover, all items have a 'I don't know' option.

	German original item	English translation	source / reasoning
1	Wie oft liest du in deiner Freizeit Bücher oder Comics?	How often do you read books or comics in your leisure time?	Lenz et al., 2021
2	Wie oft trinkst du Limonade?	How often do you drink lemonade?	Lower-income families do not eat as much healthily as wealthier families do (Fakete et al., 2016).
3	Hast du ein Zimmer für dich allein?	Do you have a room on your own?	Bos et al., 2016; Lenz et al., 2021; Mang et al., 2021; Wagner et al., 2009
4	Gibt es bei dir zu Hause Musikinstrumente?	Do you have any musical instruments at home?	Mang et al., 2021
5	Hat deine Familie einen Rasenmäher oder einen Rasenmähroboter?	Does your family have a lawn mower or a robotic lawn mower?	Beese et al., 2022; Schaufelberger et al., 2024
6	Gehst du in einen Sportverein?	Do you belong to a sports club?	Beese et al., 2022
7	Gehst du mit deiner Familie ins Theater, Kino oder ins Museum?	Do you go to the theater, cinema, or museum with your family?	Beese et al., 2022; Holz, 2006
8	Warst du letztes Jahr mindestens eine Woche im Urlaub?	Did you go on vacation for at least one week last year?	Andresen et al., 2020; Beese et al., 2022
9	Lesen deine Eltern Bücher?	Do your parents read books?	Solga & Heisig, 2015.
10	Welche Berufe haben deine Eltern?	What do your parents do for a living?	Mang et al., 2021

Furthermore, based on our data, we see the necessity to critically discuss the use of measures like the social index. Both the social index and parents' occupation are commonly used as predictors for the children's SES in Germany. Because of the opposite polarity in their definition, it is assumed that the HISEI and the social index correlate negatively. However, our results differ from this expectation ($r_{\text{occupation and social index}} = .006$; $p = .940$; $N = 160$), as no correlation could be proven. This contrasting outcome should be investigated further, as it may indicate that a school's social index reflects its actual student body only to a limited extent, even when the school is viewed as a whole. One possible explanation for this conflict is that although the social index uses data on the proportion of children in the local area who receive social benefits, it does not consider the proportion of benefit recipients who attend the school (Schräpler & Jeworutzki, 2021).

Outlook

Data collection of the main study is currently being completed. The final number of participants is satisfactory, but we encountered the problem that mainly schools with an average social index

participated in our study. In the final step, we will compare the effect of digital gamification on content knowledge gain and motivation for groups with varying SES.

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Learning Science Through Multimodal Representations

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There is growing agreement that guided inquiry and multimodal representations support students' meaning making in science. Grounded in Lemke's social-semiotic perspective and sociocultural views on collective sense-making, this study employs a case study approach across three year 5 classes in a Fijian primary school. Data was collected through learning space observations and Talanoa, a culturally appropriate qualitative data collection approach and methodology in Pacific contexts. Data was thematically analysed with findings showing that multimodal representations enhanced students' cognitive engagement by contextualising their learning of scientific concepts. Data highlighted improved affective engagement through the use of culturally relevant representations. Furthermore, Talanoa showed that sharing stories and reflecting collaboratively with peers deepened students' understanding of science concepts. The findings also revealed the key role that teachers play in scaffolding the meaning making process. These findings provide valuable insights for science educators into leveraging multimodal and culturally relevant strategies to enhance students' meaning making in scientific activities.

Keywords: Multimodal representations, Science, Engagement, Talanoa

Introduction

There is growing research interest in the meaning making process of science activities and concepts and the use of multimodal representations that support learners. Multimodal is defined as "the practice in science discourse of coordinating different modes to represent complex claims and evidence, where textual, mathematical and visual modes are integrated to explain and justify findings" (Waldrip & Prain, 2013, p. 15). In this study, the term 'multimodal' will be used to refer to a combination of more than one mode in representing scientific concepts. There is now evidence that encouraging all learners of science to generate their own representations to demonstrate their knowledge and understandings, construct a logical scientific argument and show the reasoning that they have used to arrive at a particular conclusion (Chand, 2019; Greeno & Hall, 1997; Waldrip & Prain, 2011).

The study is guided by a social semiotic perspective of multimodal representation to enhance meaning making (diSessa, 2004; Lemke, 2003) and socio-cultural theory (Vygotsky, 1978). Researchers are in consensus that learning outcomes of science learners improve with the integration of multimodal representations (Andersen & Munksby, 2018; Tytler et al., 2013).

The authors highlight the importance of multimodal and culturally responsive pedagogies in science to better support all learners, recognising that much of the current scholarly literature on the use of multimodal representations, have been pursued mainly in developed, western settings. The need to establish culturally appropriate practices when exploring student and teachers' knowledge and understandings of science concepts is critical. This study is informed by the Talanoa methodology (Vaioleti, 2006) to seek answers to the questions:

The paper examines the use of multimodality in the meaning making process in science by answering the questions:

1. How does the use of multimodal teaching strategies influence student engagement?

2. What role do the teachers play in creating and making sense of multimodal representations?

Methodology

This study is based within a qualitative research paradigm, using a case study approach to examine the impact of multimodal representations had on the students in year 5 at a primary school in Fiji. Qualitative methods were employed for this research to capture the use of multi-modal representation in the participants' setting (Punch, 2013). Data was collected through learning space observation and Talanoa.

Talanoa is rooted in oral communication and recognised in many Pacific Island countries such as Samoa, Tonga and Fiji (Nabobo-Baba, 2006; Otunuku, 2011; Prescott, 2008). Talanoa is also considered a way to engage in dialogue or tell stories (Halapua, 2008). In this study, Talanoa was conducted with intentional openness to listen to participants' experiences (Farrelly & Nabobo-Baba, 2014) which enabled the researcher to become part of the family to listen and find solutions to the phenomena being studied.

The study involved three year 5 teachers at a Fijian urban primary school. All teachers had over 10 years of experience. The class teachers from the case study class were invited for Talanoa after the learning space observation. Chosen class represented students from diverse cultural backgrounds. From each of the three classes, 10 students ages 9-10 participated in the research.

This study did not involve intervention. The teachers of the chosen classes planned and devised an instructional context in which students' conceptual understanding and reasoning were to be challenged. During the sequence of lessons, the researcher's role was mostly that of a participatory observer. Before the study began, the first researcher acted as an observer in the class for a few lessons to familiarise herself with the operation of the class and build respect and gain the acceptance and trust of students and the teacher (Farrelly & Nabobo-Baba, 2014).

The learning activities required the students to consider possible reasons for increased flooding in Fiji in recent years. The design of the activity assimilated concepts and skills from other areas of the curriculum, notably Society and Economic Development classes (Ministry of Education Heritage and Arts, 2013), to allow students to investigate the events in relation to their own people, culture, resources and environment. As part of the instruction, the class teachers introduced a picture of flooding from a daily newspaper and facilitated the students' focus on the picture to develop a question relating to the flooding phenomena which they would like to explore. Students were asked to interpret the phenomena collaboratively and represent their understandings multimodally through using drawings with written and verbal explanations.

Ten participating students, representing each of the two collaborative groups, were invited to engage in a 30-minute Talanoa session to expand and reflect on the learning experience from the student perspective. These students were selected based on the consent provided. A further three class teachers who had previously taught the lessons observed were invited to participate in a 40–60 minute Talanoa session focusing on pedagogical decision-making and the instructional strategies employed throughout the teaching experience.

The analytic process of Talanoa transcripts and field notes from the learning space observation drew on inductive thematic analysis as outlined by Braun and Clarke (2006). This involved multiple close readings of transcripts, the creation of preliminary codes, and the iterative refinement of patterns across the dataset. Particular attention was paid to culturally embedded language and the contextual meanings conveyed during Talanoa and subsequent verification

discussions, supporting accurate interpretation of culturally specific expressions and concepts (Vaioleti, 2006).

Trustworthiness of the data was enhanced through collaborative analysis by Researchers One and Three, both of whom identify as Pacific People and possess contextual and cultural knowledge relevant to the study. This shared positionality supported culturally informed interpretation and enabled systematic cross-checking of themes and insights. Such collaborative sense-making helped to minimise the influence of individual subjectivity and strengthened the credibility of the findings. Throughout the analysis, the focus remained firmly aligned with the research questions by exploring the ways teachers articulated cultural knowledge as: (1) How does the use of multimodal teaching strategies influence student engagement? and (2) What role do the teachers play in creating and making sense of multimodal representations?

Findings

The study identified that teachers' planning was prescribed by the curriculum with little emphasis on the use of varied representational modes in their learning spaces. However, actual teaching provided intentional opportunities for students to display their conceptual understanding through multiple modes.

The findings of this study indicate that the use of multimodal teaching strategies positively influenced students' engagement in science learning, while teachers played a central role in designing, modelling, and scaffolding multimodal representations to support meaning-making. When students were provided with space and opportunities to represent their understanding through multiple modes such as drawings, diagrams, charts, written text, and Talanoa demonstrated increased engagement.

Teachers reported that multimodal approaches generated excitement and enthusiasm among students, particularly when culturally familiar modes were incorporated into science learning. There was a high level of affective engagement. Students expressed enjoyment and a sense of pride when constructing drawings and charts, and when sharing their ideas through Talanoa. One student stated, "I always feel good when we are asked to draw and share our stories (S10) while another commented, "we prepare charts and do drawings, it's fun" (S6). Teachers similarly observed that students were highly motivated during multimodal activities, noting that students wanted to create their best work and were more willing to participate when drawing and discussion were included (T1).

In addition to affective engagement, multimodal teaching strategies support deeper cognitive engagement. Teachers shared that students were better able to reason, critique their learning, and explain scientific concepts when they used different modes of representation to learn and present their understanding. The construction of representations allowed students to break down complex phenomena into more manageable components, which supported analysis and synthesis of information. Teachers facilitated this process by guiding students to represent scientific ideas through structured approaches "using separate diagrams to illustrate causes, effects, and solutions related to phenomena like flooding" (T3). This approach supported students in organising their thinking and developing clearer explanations. Student evidence further demonstrated increased conceptual understanding and scientific language use, with students sharing that they had "learnt new scientific terms and could now explain the concept of flooding and its impacts on their people" (S7). The emotional story associated with flooding was also shared during Talanoa with both participating students and teachers.

Engagement was also enhanced through multimodal strategies, particularly through the use of Talanoa as a communicative practice. Teachers reported that students were more engaged and confident when sharing their learning through Talanoa (T1), as it created a safe and familiar space for discussion (T2). Through these interactions, students collaboratively shared personal stories, listened to their peers, and made connections between lived experiences and scientific concepts. As evidenced from the findings, students enjoyed engaging collaboratively in learning and sharing their understanding, "I like creating drawings with others" (S8) and having Talanoa in our science class" (S5). The findings showed that Talanoa supported deeper discussions, allowing students to collaboratively construct understanding and relate scientific ideas to other phenomena and contexts.

Teachers played a crucial role in enabling students to engage meaningfully with multimodal representations. Although teachers indicated that lesson planning was often driven by curriculum requirements with a stronger focus on content coverage than on representational modes, they made intentional decisions during instructions to integrate multimodal representations. Teachers described selecting representational modes responsively based on the learning context, "the phenomenon being explored, and the students present in the classroom" (T1). Some teachers deliberately aligned task outcomes with particular representations and considered cultural appropriateness when choosing modes, noting that "drawing, Talanoa, and storytelling were especially effective for engaging students" (T2).

Teachers also acted as expert models by demonstrating how different representations could be constructed and explaining why specific modes were appropriate for sharing meaning. It was evident that modelling the use of diagrams, labels, gestures and written texts was beneficial to the students. Teachers helped students understand how representations functioned as tools for scientific communication (T3). Alongside modelling, teachers scaffolded students' representational skill through explicit instruction, questioning, and gradual release of responsibility as students engaged in representation contraction. Teachers shared that "students were initially provided with clear guidance on which representations to use" (T1), and as they developed confidence, they were encouraged to explore additional modes independently.

Culturally responsive practices were a prominent feature of teachers' approaches to multimodal teaching. Teachers recognised drawing and Talanoa as culturally embedded practices and intentionally incorporated them into science lessons. One teacher described "drawing and design-making as cultural skills" (T4), while Talanoa was identified as a "practice grounded in cultural values and commonly used to share experiences and ideas" (T3). By allowing the use of these practices within science learning, teachers supported students to engage more confidently and meaningfully with scientific concepts while maintaining strong connections to their cultural identities.

Overall, the findings demonstrate that multimodal teaching strategies enhance student engagement by fostering enjoyment, supporting deeper thinking, and encouraging collaborative learning. Teachers played a key role in shaping these outcomes through their responsive planning, modelling of expert representations, scaffolding of students' meaning making, and integration of culturally meaningful modes of communication. These practices collectively supported students to use multimodal representations as effective tools for understanding and communicating scientific ideas.

Discussion And Implications

The findings of this study demonstrate that multimodal teaching strategies enhance student engagement and support meaningful science learning when they are used appropriately in science

learning. Although teachers' planning was largely prescribed by curriculum requirements, pedagogical decisions and reasoning created opportunities for students to express understanding through drawings, diagrams, charts, written texts, verbal explanations and Talanoa. This aligns with research which positions science learning as inherently multimodal, where meaning is constructed through the coordination of visual representations such as drawings, verbal, and gestural representations (Chand, 2019; Jewitt et al., 2016; Ainsworth, 2006). Providing multimodal representations enabled students to engage effectively, as evidenced by enjoyment, enthusiasm, and work completion, a factor strongly associated with sustained engagement in learning (Fredricks et al., 2004).

The findings also indicate that multimodal practices supported deeper cognitive engagement. Students' construction of drawings and diagrams allowed them to break down complex phenomena, organise relationships between elements of the task, and articulate explanations more clearly. Such reasoning processes are central to scientific meaning-making and are strengthened when students actively construct and refine representations rather than simply receiving information (Tytler et al., 2013; Cirkony et al., 2022). Decisions regarding what to include, how to organise components, and how relationships are shown represent important sites of conceptual development.

The findings extend our understanding of the use of multimodal representations and integration of Talanoa as a culturally responsive mode. The use of Talanoa as an informal conversation through which students shared their stories and relating it to their context was effective. It enabled students to unlock the richness of experience and knowledge embedded in a socio-cultural environment (Halapua, 2008). On the one hand, Talanoa gave insight of students' understanding and reasoning of science concepts, while on the other hand, it captured the emotions associated with the phenomenon being studied. We suggest that scientific terms be introduced slowly while engaging in Talanoa to link scientific concepts to real life situations.

The findings indicate that affective and cognitive engagement of students improved with the use of multimodal and culturally relevant representations. Findings indicated that students showed an increased level of interest in exploring the given phenomenon. Drawing and Talanoa were the most common representations used, indicating the cultural connection these modes have with the context of the study. The construction of appropriate and logical diagrams, the inclusion and placement of components, showed the students' ability to convey their mental representations on each drawing. This aligns with Tytler et al. (2013) who asserted that reasoning happens when students make representational selections and decide appropriate size or how to put different components together, hence improving the meaning making process.

A key implication of these findings is the central role of teacher expertise in designing, modelling, and scaffolding multimodal representations. Teachers functioned as expert guides, modelling how representations operate as scientific tools and supporting the meaning making process for students. This highlights the importance of teacher professional learning that moves beyond content coverage to include representational pedagogy. Supporting teachers to intentionally plan for multimodality as well as choosing culturally appropriate representations can strengthen student engagement and conceptual understanding.

Conclusion

This study identifies and analyses the processes through which primary school students strengthen their conceptual understanding and scientific reasoning. It is evident that multimodal representations, including those with cultural connectedness, have a positive impact on students' cognitive and affective engagement. While the authors acknowledge the small sample size of

students involved in the learning space observations limits the generalisability of the findings, this research highlights the broader question of the need to consider culturally sensitive forms of expression as part of the overall conception of a learning environment designed to elicit student thinking. Valuing diverse modes of knowledge representation in science can enhance Indigenous learners' engagement, understanding, and cultural affirmation (Chand, 2019).

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Designing Video-Tutorials As A Supporting Tool In The Experimentation Process

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Interactive video-tutorials represent a promising tool for enhancing science education by supporting learners in acquiring procedural competences critical for scientific literacy. Unlike traditional explanatory videos, interactive video-tutorials are action-guiding in nature, providing step-by-step instructions to help students replicate actions and engage in hands-on scientific practices. This study focuses on identifying design criteria for effective interactive video-tutorials that support learners in the proper use of measuring devices, such as thermometers, scales, stopwatches, and rulers, during experimental processes.
Using Kulgemeyer's (2020) framework for effective explanatory videos as a foundation, this research adapts and extends the criteria to meet the specific demands of interactive video-tutorials. To achieve this, the criteria were critically reviewed for their applicability to action-guiding content and adjustments were made to address the unique challenges of designing interactive video-tutorials for primary learners. These include emphasising clarity, coherence, age-appropriate content, and accessible language, while maintaining the authenticity of the experimentation process.
The results demonstrate how interactive video-tutorials should be designed to integrate digital media into hands-on learning, enabling learners to actively engage in measuring processes in experimental contexts and develop critical skills. These tools offer a means of bridging the gap between digital resources and authentic scientific practices in primary education. Future research will explore the effectiveness of interactive video-tutorials that follow the identified design criteria across educational contexts and their potential to foster independence in experimental tasks, contributing to the development of innovative strategies for science education.

Keywords: Digital Learning, Instructional Design, Primary Science Education

Introduction

The acquisition of scientific competences is central to fostering scientific literacy, a key goal of science education. Scientific literacy not only forms the foundation for individual personal development but also equips learners with the knowledge necessary to participate actively in society. To foster scientific literacy, it is essential to identify the competences learners must develop and to explore how these can be effectively enhanced within school contexts. The OECD's definition of scientific literacy**,** as outlined in the PISA (2018) framework, further underscores this by categorising it into content knowledge, procedural knowledge, and epistemic knowledge. While content knowledge focuses on factual and conceptual understanding, and epistemic knowledge on the processes behind acquiring scientific knowledge, procedural knowledge encompasses the practices of science (*PISA for Development Assessment and Analytical Framework*, 2018). To foster these competences, students must engage in authentic learning environments and participate actively in scientific practices, such as conducting experiments. This highlights the critical role of experiments in science education (Osborne, 2014).
However, despite their critical role, experimental activities can pose considerable barriers for learners, including methodological, communicative, and cognitive demands (Stinken-Rösner et al., 2023). The integration of digital tools has the potential to overcome barriers and to support these experimental practices in learning settings, provided they maintain the authenticity of the

experimentation process.
As digital media become increasingly integral to educational contexts, explanatory videos have gained prominence as tools to support learning (Kulgemeyer & Wittwer, 2023). While explanatory videos are commonly used in schools to support the acquisition of content knowledge, they are primarily designed for passive viewing (Wolf, 2015), making them less suited to fostering procedural competences that require active engagement. In contrast, video-tutorials, with their action-guiding character (Wolf, 2015), offer step-by-step instructions that could encourage learners to imitate demonstrated actions. This unique characteristic positions video-tutorials as a promising digital tool for supporting the development of procedural skills, such as handling measurement devices, recording data, and conducting experiments independently. Building on this approach, interactive video-tutorials extend traditional formats by integrating learner-controlled decision points that actively involve the viewers during the experimentation process. Rather than following a fixed linear sequence, learners can interact with interactive video-tutorials to access support that is relevant to their current task. These forms of interactivity are assumed to support active and self-regulated engagement, which is considered essential for the acquisition of procedural knowledge in experimental contexts (Chi & Wiley, 2014). By bridging the gap between digital resources and hands-on learning, interactive video-tutorials can provide an innovative way to engage students in scientific practices and enhance their experimental competences.
The importance of investigating the use of interactive video-tutorials is twofold. First, the increasing integration of digital media into classrooms requires a deeper understanding of how to design and implement these tools effectively. Second, at primary school level, where the foundation for scientific literacy is established, fostering the acquisition of scientific competences, especially procedural ones, through innovative methods is paramount. Despite the potential of interactive video-tutorials to support experimentation, their application in primary education remains unexplored. This research aims to address this gap, focusing on the systematic identification of design criteria for interactive video-tutorials to promote scientific competences at the primary level. These design criteria are theoretically derived and defined based on established frameworks for instructional design, multimedia learning, and research on experimental and measuring competences.

Theoretical Framework

The use of digital media, especially media such as explanatory videos, plays a central role both in everyday lives of students and in school contexts. With regard to teaching contexts, there are numerous possible applications, such as in flipped classroom settings or the production of videos by students as a presentation tool. It can be assumed that the relevance of explanatory videos for science lessons will increase in the future (Kulgemeyer, 2020).
Explanatory videos are typically defined as self-produced short films designed to explain complex concepts. However, in contrast to these classic explanatory videos, (interactive) video-tutorials are instructional in nature. Their defining characteristic is their action-guiding purpose, offering step-by-step instructions that encourage viewers to replicate the demonstrated actions (Wolf, 2015). While explanatory videos have been extensively researched, the potential of (interactive) video-tutorials as a medium to support hands-on-activities in science education remains unexplored. Interactive video-tutorials are particularly well-suited to contexts that require hands-on-activities, such as scientific experimentation, as they allow learners to access procedural guidance in close temporal and functional proximity to their own actions. Experiments are a cornerstone of science education and involve numerous practical steps, requiring students to develop various experimental competences (Tesch & Duit, 2004). Experimental processes can be categorised into three overarching phases: planning, performing, and evaluating experiments,

each of them requiring specific competences (Schreiber et al., 2009). Supporting the acquisition of these competences requires instructional formats that can be flexibly aligned with different phases of the experimentation process and with learners' situational needs. Interactive video-tutorials on the use of measuring devices appear to be particularly suitable, as they address competences that are independent of the individual experiment. Also, learners at the primary school level are faced with the challenge of not only familiarising themselves with relevant measuring devices and the respective quantities and units, but also having to apply them for the first time in experimental settings to differentiate subjective sensory impressions from objectively measured physical quantities (GDSU, 2013).

In the context of experimental learning, instructional support needs to be closely aligned with the procedural structure of the measuring process. Learners are required to make decisions and perform actions at the different stages of measurements to foster sub-competences. Accordingly, instructional approaches aimed at experimental competences should allow learners to access guidance that corresponds to their current phase within this process. However, the effectiveness of interactive video-tutorials, just like that of explanatory videos, depends heavily on their design. To ensure they support learning effectively, they must adhere to key instructional design principles (Kulgemeyer & Wittwer, 2023) and integrate seamlessly into the broader learning process.

Aims And Research Questions

The research presented focuses on identifying design criteria for interactive video-tutorials that effectively support learners in using measuring devices during experimental processes. The overarching aim is to explore how these interactive video-tutorials can best facilitate the development of experimentation competences, with a particular emphasis on guiding students through the proper choosing and handling of measuring devices as well as accurate data acquisition. We address the following research question:

What design criteria are essential for creating interactive video-tutorials that support the handling of measurement devices in experimental contexts?

Methods And Relevant Research Literature

The study employed a deductive research approach, drawing on established research literature on instructional video design as well as on models of experimental and measuring competences. On this basis, both relevant measuring-related sub-competences and design criteria for interactive video-tutorials were systematically derived and defined. The focus was placed on relating the structural characteristics of measuring processes in experimental contexts to suitable instructional design criteria for interactive video-tutorials.

Research literature on experimental competences was analysed in order to conceptualise experiments as a structured scientific practice comprising the phases of planning, performing, and evaluating experiments (Nawrath et al., 2011; Schreiber et al., 2009). These models provide a process-oriented framework that describes the sequence and structure of experimental processes in science education as well as certain experimental competences within each phase. Building on these models, measuring processes were conceptualised as a central scientific practice that occurs within all three phases of the experimentation process (Murer et al., 2025). This analysis informed the alignment of the interactive video-tutorials with relevant decision points and actions that learners need to successfully select measuring devices, read and record measured values, and represent data correctly.

Kulgemeyer's (2020) framework for effective explanatory videos informed the identification of design criteria, particularly in relation to structuring and tailoring interactive video-tutorials to

support the named measuring competences throughout the three overarching phases of the experimentation process. It is grounded in principles derived from empirical research on instructional explanations and findings about multimedia learning. The concluding framework outlines 14 key criteria to guide the production of explanatory videos that are both scientifically accurate and pedagogically effective. These criteria fall into seven main categories: structure, adaption, tools for adaption, minimal explanation, highlighting relevancy, follow-up learning tasks and new, complex principles (Kulgemeyer, 2020). All criteria were critically analysed with regard to a possible implementation for interactive video-tutorials that support the handling of measuring devices in experimental contexts. Particular attention must be paid to the extent to which the criteria can be adapted to learner-controlled, non-linear digital learning formats such as interactive video-tutorials that allow for situational access to instructional support.
Bringing together both perspectives, measuring related competences and instructional design criteria were systematically related to each other in order to inform the design of interactive video-tutorials that are aligned with the measuring process and tailored to the demands of measuring activities in primary science education.

Results

Table 1 specifies measuring related sub-competences within the model of experimentation in primary school settings.

Table 1. Measuring Sub-Competences in the experimentation process in primary school settings.

Measuring Sub-Competences	Planning	Performing	Evaluating
SC1: Learners know measuring devices and can name them.	✓	×	×
SC2: Learners indicate which measuring device to use to measure different quantities.	✓	×	x
SC3: Leaners know corresponding units for quantities and can name them.	✓	×	✓
SC4: Learners select suitable measuring devices in specific experimental situations.	✓	✓	×
SC5: Learners select suitable measuring devices with regard to the measuring range.	✓	✓	×
SC6: Learners correctly read measured values from different measuring devices for the same quantity.	×	✓	×
SC7: Learners correctly read measured values while taking a parallax error into account.	×	✓	×
SC8: Learners document the measured values taken.	×	✓	×
SC9: Learners correctly transfer measured/documented values into a table.	×	×	✓

In the phase of planning, learners must decide which measuring device is suitable for the

measuring process based on their knowledge about measuring devices, quantities and units. While performing the experiment, learners must correctly use each measuring device as well as correctly read and document measured values. For transparency and traceability, the documented values must then be visualised in a table during the evaluation phase (Reuter & Stinken-Rösner, submitted).

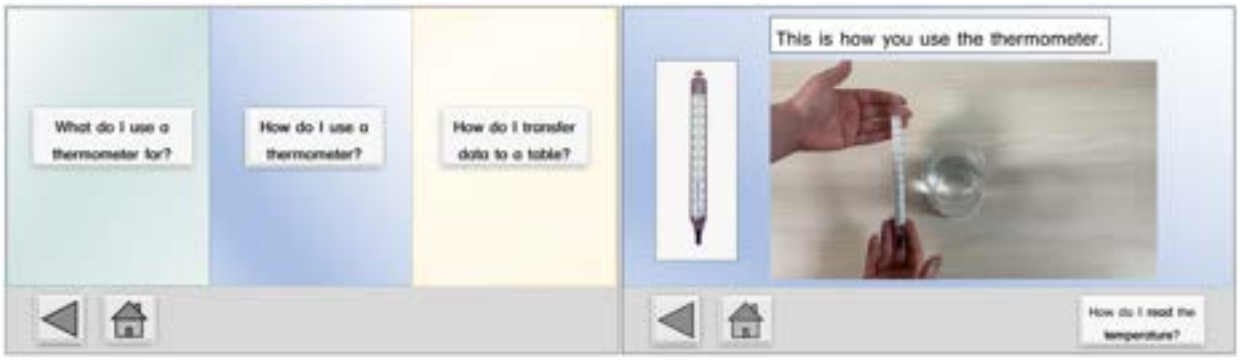
Table 2 shows the extent to which the criteria for effective explanatory videos (Kulgemeyer, 2020) can be applied to the creation of interactive video-tutorials to fit their action-guided purpose as well as our target group (primary school children).

Table 2. Implications for the design of the interactive video-tutorials based on video criteria (Kulgemeyer, 2020).

Factors	Feature	Implications for interactive video-tutorials
Structure	Rule-example/example-rule	Interactive video-tutorials follow the example-rule structure by first demonstrating its use on a selected measuring device and then deriving general rules.
	Summarising	Interactive video-tutorials are divided into individual sections for clarity, making a summary about the whole process redundant.
Adaption	Adaption to prior knowledge, misconceptions and interest	Interactive video-tutorials focus on familiar devices and quantities (mass, time, length, temperature) and address typical handling errors.
Tools for adaption	Examples	Interactive video-tutorials show standard devices (e.g., digital and analogue scales) for each measurement type.
	Analogies and models	Not necessary with regard to interactive video-tutorials.
	Representation forms and demonstration	Interactive video-tutorials demonstrate exact procedures for using each device.
	Level of language	Interactive video-tutorials use simple, familiar professional language, avoiding unnecessary terms.
	Level of mathematisation	Interactive video-tutorials focus is on familiar units (e.g., kg, °C) and numbers ranges for clarity.
Minimal explanation	Avoiding digressions	Interactive video-tutorials focus strictly on core tasks (e.g., handling of specific measuring devices).
	High coherence	Interactive video-tutorials for each measurement device follow the same structure.
Highlighting relevancy	Highlighting relevancy	Viewing is optional; learners decide which interactive video-tutorials they need and are therefore relevant.
	Direct addressing	Interactive video-tutorials use the second person singular.
Follow-up learning tasks	Follow-up learning tasks	Hands-on activities are the motivation for using interactive video-tutorials, eliminating the need for separate follow-up tasks.
New, complex principles	New, complex principle	Interactive video-tutorials introduce new measurement actions rather than new principles.

In interactive video-tutorials, the example-rule structure comes naturally, as they demonstrate individual steps of the measurement process. Similarly, demonstrations and direct addressing are inherent to the tutorial format.
Certain criteria, like summarising and follow-up learning tasks, are unnecessary. The interactive video-tutorials are divided into clear steps, according to relevant actions in the measuring process, making summaries redundant, and hands-on activities are the actual starting point for utilisation. Other criteria require specification. Tools for adaption focus on familiar devices, accessible language, and appropriate mathematisation to match learners' prior knowledge. Coherence is ensured by following an idealised measuring process as well as using the same structure for multiple tutorials. Rather than introducing new principles, the interactive video-tutorials teach new actions in order to foster measuring competences.
The resulting criteria were used to design an interactive video-tutorial for relevant measurement devices at primary school level to measure length, time, mass, and temperature. Exemplary screenshots for the use of thermometers in the measurement process are shown in Figure 1.

Figure 1. Exemplary screenshots from the interactive video-tutorials.



When starting the measuring process, viewers must first decide which is the suitable measuring device for the quantity to be measured. For example, a thermometer should be selected for temperature measurements. In the shown example (see Figure 1, left), viewers can choose between three options: To obtain information on what a thermometer can be used for (planning), information on how to use a thermometer (performing) or how to transfer collected data to a table (evaluating). This directly aligns with the three overarching phases of the measuring process. Within these sections, further decisions aligned to the sub-competences can be made. In the planning phase (option "What do I use a thermometer for?"), learners are presented with different types of thermometers to support their decision on which instrument is suitable for a specific measuring situation and measuring range. Once a suitable thermometer has been selected, the interactive video-tutorial continues with thermometer-specific guidance. Learners can watch a short video sequence on the use of a thermometer in an exemplary measuring situation and then continue on how to correctly read the temperature (see Figure 1, right).

Outlook

The interactive video-tutorials developed in this project constitute a first step towards supporting measuring-related competences in primary science education. The next phase of research focuses on embedding the interactive video-tutorials into an experimental learning environment on sensory illusions. These provide authentic and motivating experimental situations in which learners are required to measure physical quantities in order to contrast subjective sensory impressions with objective, measured data. Within this setting, the interactive video-tutorials are integrated as a situational support that learners access during the phases of the measuring process. To investigate the effectiveness of the interactive video-tutorials, a pre-post study design is employed using a competency test targeting the named measuring sub-competences (Reuter &

Stinken-Rösner, submitted). This design allows for the systematic analysis of learners' competence development and provides insights into how interactive video-tutorials can contribute to fostering procedural competences in primary science education. The first empirical studies are planned for 2026.

Conclusions

This study highlights the potential of interactive video-tutorials as a valuable tool for enhancing science education, particularly at the primary school level. Unlike traditional explanatory videos, interactive video-tutorials are action-guiding in nature, providing step-by-step instructions that enable learners to replicate actions and acquire essential procedural skills. Given the importance of experiments in fostering scientific literacy, the integration of well-designed interactive video-tutorials could support learners in developing measuring competences while leveraging digital media to promote authentic scientific learning. By adhering to well-defined design criteria, these tools have the potential to enhance student engagement and foster the acquisition of vital experimental skills.

Using Kulgemeyer's (2020) framework for effective explanatory videos as a foundation, this study adapted and extended the criteria to address the specific challenges of designing action-guiding tutorials. Additionally, the interactive video-tutorials focus on age-appropriate measuring devices and accessible language to ensure clarity and usability and to adapt to prior knowledge. The application of these criteria was demonstrated through the development of an interactive video-tutorial for common measuring devices such as thermometers, scales, stopwatches, and rulers. By addressing specific steps in the measuring process, such as selecting, operating, and documenting with these devices, the interactive video-tutorial provides targeted support for learners, helping them to acquire procedural knowledge and improve their measuring competences.

Future research will focus on evaluating the effectiveness of interactive video-tutorials in diverse educational contexts, particularly their impact on learners' procedural competences and their ability to foster independence in experimental tasks.

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Creativity and Programming Essentials as Skills for a Transitioning Digital World

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In a fast-paced technological world, children need to be equipped with skills that allow them to keep that pace and to act accordingly. Therefore, a basic understanding in technology as well as creativity might be helpful. This enables children to find their way in a digital world that is developing at a very fast pace and also to draw on their own expertise and creative solutions to problems. It is advisable to address these skills in elementary school and lay the necessary basics here.

This study therefore examines the question of how creative and algorithmic thinking are connected. In addition, an attempt was made to develop a creative learning unit to train basic programming skills. As a basis for addressing this topic, a suitable test instrument was designed and evaluated to assess the creativity of elementary school children in the context of a learning unit on programming.

The results show that the test instrument for creativity was successfully evaluated. The results revealed that the elementary school children surveyed had almost no prior knowledge with respect to programming skills, but these skills improved significantly with the learning unit proposed in the present study.

Keywords: Computational Thinking; Early Science Education; Play and Science Learning

Introduction

In a fast-developing, increasingly digital world, a fundamental understanding of digitality and the associated processes are essential. This includes a basic understanding of the fundamental functionality of programming and the ability to think creatively and develop innovative approaches and problem-solving strategies. Creativity is described as a 21st-century skill for good reason, especially in the context of unpredictable new challenges. At this point, the question rightly arises as to where and how such skills can be examined and developed. Following the results of the latest PISA study from 2022, the consortium is also calling for creativity to be promoted in schools (Diedrich et al., 2024). Particularly in natural science and social science education in elementary school, there is seen to be special potential for creative educational processes (Holzapfel et al., 2022; Rau-Patschke et al., 2024). Further the results of the International Computer and Information Literacy Study (ICILS) from 2023 show a lack of both – computer and information literacy skills at higher proficiency levels, including operationalizing solutions (Fraillon, 2024). Digital learning environments open up a wide range of opportunities to challenge and support children technologically and in developing IT skills, as well as in the ability to think creatively and generate innovative ideas.

Agreeing with the Informatics for All Coalition that computer science education should start in elementary school (Caspersen et al., 2018), we designed a learning setting that combines creativity and computational thinking skills in elementary school.

Theoretical Framework

In the study presented here, both aspects are combined in an intervention for creative programming for elementary school children that is tested and evaluated. Now that an initial small feasibility study has been carried out and the project has been confirmed (Holzapfel et al., 2024), the focus will be on the relations between the two constructs of programming experience and creativity. Therefore, both aspects will be discussed theoretically below.

Computer Science As An Essential Skill For An Innovative World

Computer science and creativity are closely linked. Modeling activities, for example, require and simultaneously promote the application of creativity (Schubert & Schwill, 2011). Through computer science ways of thinking, working and acting, one's own ideas become functional programs, games or entire interactive systems that take on a perceptible form. The promotion of creativity in computer science lessons is therefore an important goal which can also be transferred to the technical perspective of science education in elementary school (Hubwieser, 2007). Learning environments therefore open up a wide range of opportunities to challenge and encourage children both technologically and creatively. Robot-assisted settings in particular combine creative, reflective, and technical requirements, allowing creative thinking to be immediately visible in action.

Robotic learning environments promote technical, creative, and social learning in combination (Bers, 2008). They follow the principle of technological fluency—that is the ability to use technologies creatively and purposefully, like a language. Programming skills expand children's expressive possibilities: sensors, movement patterns, and audiovisual elements can be embedded in self-selected themes and narratives. Tactile systems such as BlueBots enable intuitive, action-oriented access in the sense of “hands-on” pedagogy (Bers, 2008, p. 48). Digital storytelling with robots for example combines technology, language, and individual design. Children program robots, assign them roles, and stage stories—an expression of digital creativity (Bers, 2008; Sawyer & Henriksen, 2024).

Creatively Facing New Challenges

In order to be able to make statements about children's creativity, a suitable test instrument is needed. In line with current research, creativity was operationalized as first step for this project (Holzapfel et al., 2022). The current discourse is clear: creativity is often operationalized as construct that is composed of divergent and convergent thinking and requires both equally (Runco & Jaeger, 2012). Divergent thinking - that is, the flexible, imaginative variation of approaches to solutions - is considered central to this (Cropley, 2006). Guilford (1967) also emphasizes the importance of convergent thinking, which structures selection, evaluation, and decision-making processes. In other words, those who think creatively think innovative and different, but also solution-oriented and goal-oriented (Sternberg & Lubart, 1998).

Creativity research often refers to four sub-areas of creativity: the creative person, the creative process, the creative product and the creative environment (Rhodes, 1961). These sub-areas are all relevant for teaching and learning. The creative person can therefore be a teacher or student, the creative product a learning outcome, the creative environment an appropriately designed classroom and the creative process can be a learning process (Bliersbach & Reiners, 2017).

The project presented here considers all four areas, with the focus being on the creative person, i.e., the creative students.

Purpose Of The Study

Since creativity and the basics of computer science are considered important skills in a modern, fast-paced world, the question arises as to the status quo of these two skills among children of elementary school age. Furthermore, it seems important to examine the interaction between these skills and to develop ways of teaching them. This study therefore investigated the following research questions.

As can be deduced from the theory, creativity is a very complex construct that can be roughly described by specific abilities in both divergent and convergent thinking. In order to make a statement about the creativity of elementary school students, it must be possible to operationalize and measure it. The first research question is therefore:

> RQ 1: How can creativity of elementary school students be measured?

The operationalizability of the construct of creativity should be considered specifically in the context of the basic computer science education of elementary school students. In addition, the question arises as to what prior knowledge in basic programming skills the children have and whether it is possible to develop a successful intervention to promote basic programming skills. This leads to the following question:

> RQ 2: Is the intervention effective for promoting basic programming skills? Are there gender differences or differences between the grades?

In a next step, the question occurs as to the connections between creativity and basic programming skills. The corresponding research question is:

> RQ 3: Is there a relation between creativity (i.e., divergent/convergent thinking) and algorithmic thinking?

Methods

To answer these questions, a half day intervention for the floor-robot BlueBot was developed, and data on basic programming skills (adapted from Zapata et al., 2021), creative thinking (adapted from Landmann et al., 2014 and Torrance, 1966) and demographic information and control variables (joy of learning, use of digital media, interest in technology, age, gender) were collected in a paper-pencil questionnaire in a pre-post design. In addition to this quantitative data, qualitative data (photos, videos and observation sheets) was also collected, but will not be discussed in detail here. In the creative learning intervention, the children were asked to work in tandems to invent a story on a topic of their choice, and to program the robot so that it acts according to the story. To gain initial experience in this process and to express this, the children were given the task of creating a field for the BlueBot on which it would follow a programmed, predetermined path. The tandems were able to design the field individually from wooden puzzle tiles. Each tandem received the following tiles: a start and finish tile, 5 tiles prepared with blackboard varnish, which the children could paint as they wished, and 13 blank tiles on which the BlueBot was allowed to move.

Sample

A total of $N = 405$ pupils from grades two to four from elementary schools in Germany (Ø 8.29 years; 202 girls and 193 boys, 3 non-binary/other genders, 7 missing values) were surveyed. Participation was voluntary and school management, and all parents gave their consent.

Results

With regard to *research question one*, it can be stated that the scaling of creativity was successfully calculated using SPSS. Two parameters, divergent and convergent thinking, were determined using collected data. Divergent thinking was measured via three scales, two figural and one verbal scale, based on Torrance (1966). As with Torrance (1966), a value for Originality, Fluency and Flexibility was determined for each scale. Originality stands for the uniqueness or rarity of the idea, fluency for the number of ideas of a person, and flexibility for the number of different ideas of a person. The values determined for all three scales were converted into an overall value for divergent thinking and then were z-standardized. For convergent thinking, a scale of eight items based on the Compound Remote Associates Test (Landmann et al., 2014) was used and a sum score was calculated. For uniformity, this sum score was also converted into a z-standardization and forms the value for convergent thinking. Based on these two values, four subgroups were formed using a median split. The median split was calculated once for the value of the divergent thinking and again for the value of the convergent thinking. The sample showed a relatively equal split into four groups: low convergent and divergent thinking (n= 104), low convergent and high divergent thinking (n= 94), high convergent and low divergent thinking (n= 98), and high scores in convergent and divergent thinking (n= 109). The group with high values in divergent and convergent thinking can be described as creative based on the literature (Holzapfel et al., 2024).

Regarding to the *second research question*, it can be stated that the children learned significantly overall ($t(399) = -11.24$, $p < .001$, Cohen's $d = -.562$). The prior knowledge was very low ($M = 1.94$, $SD = 2.16$, maximum achievable score 8) and the value of the post-test does not show a very high level of knowledge either ($M = 2.96$, $SD = 2.61$). Even though prior knowledge was very low, there was a clear increase in learning. However, there would have been further potential for improvement.

Table 1: Algorithmic thinking scores separated by grade.

Grade	alg. *(Pretest)*	alg. *(Posttest)*	alg. (*learning gain)*
2	1.38 (1.71)	2.23 (2.44)	.81 (1.73)
3	1.92 (2.29)	2.73 (2.58)	.80 (1.65)
4	2.95 (2.36)	4.63 (2.24)	1.73 (2.04)

alg. = algorithmic thinking

Descriptively, there are gender differences in the basic programming skills pretest scores (f: $M = 1.61$, $SD = 2.06$; m: $M = 2.29$, $SD = 2.23$), as well as in the posttest scores (f: $M = 2.55$, $SD = 2.55$ and m: $M = 3.39$, $SD = 2.61$), which revealed to be significant for both the pretest and the posttest (pretest: $F(1, 393) = 9.67$, $p = .002$, $\eta_p^2 = .024$, and posttest: $F(1, 391) = 10.24$, $p = .001$, $\eta_p^2 = .026$, respectively). With respect to learning gain, both for girls and boys significant results were observed (f: $t(200) = -8.14$, $p < .001$, Cohen's $d = -.574$; m: $t(191) = -7.74$, $p < .001$, Cohen's $d = -.559$), thus, both girls and boys had significant learning gain. A further analysis however did not reveal significant gender differences with respect to learning gain ($F(1, 391) = 1.174$, $p = .279$, $\eta_p^2 = .003$), indicating that girls and boys learned to the same extent.

In addition, some differences between the grades can be reported. There were significant differences between the pretest scores ($F(2, 399) = 16.68$, $p < .001$, $\eta_p^2 = .077$), as well as significant differences between the post-test scores ($F(2, 400) = 29.74$, $p < .001$, $\eta_p^2 = .129$), with higher scores in higher grades (see Table 1). Learning gain also differed significantly between grades ($F(2, 397) = 9.81$, $p < .001$, $\eta_p^2 = .047$), with the highest learning gain in grade four (see Table 1).

A comparison between children with low and high levels of creativity revealed significant differences with respect to pretest and post-test scores for algorithmic thinking (pretest: main effect "convergent thinking": $F(1, 398) = 17.85$, $p < .001$, $\eta_p^2 = .043$; main effect "divergent thinking": $F(1, 398) = 0.093$, $p = .760$, $\eta_p^2 < .001$; interaction effect: $F(1, 398) = 0.002$, $p = .963$, $\eta_p^2 < .001$; post-test: main effect "convergent thinking": $F(1, 399) = 3.53$, $p = .061$, $\eta_p^2 = .009$; main effect "divergent thinking": $F(1, 399) = 0.49$, $p = .485$, $\eta_p^2 = .001$; interaction effect: $F(1, 399) = 0.43$, $p = .514$, $\eta_p^2 = .001$). This would also address the question regarding the connection from *research question three*.

Discussion And Implications

A practicable operationalization of the creativity of elementary school students in the context of an intervention to introduce programming was demonstrated. The elementary school students surveyed had almost no prior knowledge of programming. Against the background of existing but very limited prior knowledge, it seems necessary to teach the basics, especially in view of the rapid technological development. The evaluation presented here shows that the learning unit is suitable for providing initial insights into the basics of computer science. It should be noted that there are differences between boys and girls. The boys achieved significantly higher scores in both the pretest and post-test, but there was no significant difference between boys and girls in terms of learning gains. Although this suggests that the intervention is equally suitable for boys and girls, it also shows that it did not succeed in raising girls' algorithmic thinking skills to the level of boys. In addition, there was a significant difference in algorithmic thinking between the grades. Overall, algorithmic thinking skills increase continuously from grade two to grade four with fourth graders achieving almost twice as high scores as children in grades two and three in terms of both pre- and post-test results and learning gains. It therefore appears that the intervention is most suitable for children in grade four with respect to algorithmic thinking skills. However, other constructs like for example developing interest and self-concept regarding Computer Science were not in the focus of the present study and should therefore be examined in the future.

A concrete implication for practice based on the data collected is that the synergy between creativity and programming skills is not only successful but also extremely useful and both can benefit from each other. This applies especially to convergent thinking. If we succeed in promoting this, it could probably have an impact on the algorithmic thinking. The results of this study already indicate this, but further analyses should be carried out in order to be able to make a more precise statement here.

On this assumption, further research should be conducted to repeat or extend the intervention with other learning robots in order to achieve a possibly even higher effect and also to determine whether the results of this study can be replicated or even improved upon with other robots. It would also be very informative and exciting to look at how the tandems interact with each other on the basis of the data already collected or additional studies. In this context, it would be interesting to see what influence the creativity of both children and their programming skills have on the creation and design of the stories and the coding. Further, it would also be interesting to take a closer look at the differences between the grades or genders. The results of the study

presented suggest that second and third graders may have even more difficulties with algorithmic thinking, whereas fourth graders demonstrate much better skills. Therefore, further studies should clarify whether this is only a phenomenon of the present intervention or measurement, or how and when algorithmic thinking skills need to be addressed. Further, gender differences need to be addressed more explicitly.

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Not Produced "For The Wastebasket" – Materials In The Fops Project

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The new primary schools curriculum in Austria (BMBWF, 2023) places greater emphasis on inquiry-based learning in science studies. To support teachers, the FoPs project is developing teaching materials based on four pillars. In addition to inquiry-based learning, these pillars are scientific ways of thinking and working, using concrete matter (German: die Sache) as a starting point, and the scaffolding of language. Based on a common research question, all materials enable internal differentiation in lessons. Therefore, materials based on the same research question are provided for structured inquiry (Level 1) and guided inquiry (Level 2) of inquiry-based learning. A teachers' guide is also provided. The materials were used by teachers in general studies (German: Sachunterricht) in an initial evaluation phase. To ensure the materials are used beyond the project period, a questionnaire was developed and conducted with primary school pre-service teachers on Bachelor Level. The aim was to find out what is necessary for pre-service teachers to integrate these materials into their lessons in the long term and what improvements they would like to see.

Keywords: Primary Science Instruction, Science Practices, Learning Environments,

Introduction

Basic scientific literacy should be introduced in science teaching at primary level (AAAS, 2012). In Austria there is a main subject called Sachunterricht (general studies) which includes social studies and natural sciences. The aim of this subject is to offer learning opportunities to convey concepts, promote scientific ways of thinking and working, and address nature of science. This is where FoPs ("Forschendes Lernen in der Primarstufe" that means inquiry-based learning in primary education) comes in. Three institutions are cooperating in this research and development project to promote inquiry-based learning at primary school (Nosko et al., 2025; Puddu et al., 2024). In doing so, different learning opportunities are developed based on a specific matter to promote scientific ways of thinking and working. "The soup" is one of these learning opportunities, for which teaching materials and a teachers' guide have been created. Soup powder is a quick way to make soup, and it is probably found in almost every household. Most students are familiar with it, and many learning opportunities related to chemistry, physics, social sciences or economics can be developed based on the scientific phenomenon of solubility.

Conception Of The Materials

The materials in the FoPs project are based on four pillars that are anchored in the primary school curriculum (BMBWF, 2023): a) starting with the matter at hand, b) scientific ways of thinking and working, c) the use of inquiry-based learning with varying degrees of openness and d) language support.

The Four Pillars

When Köhnlein (2022, p. 39f) writes about the "matter of general studies" (Sache), he is referring to everything that gives rise to a discussion or investigation. He is not only referring to real objects, but rather to "objects of our thinking and speaking". Matter always exists in a certain factual context. This implies that subject lessons must never focus on just one aspect of the topic.

It is important to also consider the social, environmental, technical or historical aspects of a matter.

Scientific ways of thinking and working can be seen as diverse methods of encountering new knowledge. This gives pupils in science lessons the opportunity to engage intensively with matters and explore them in depth. According to Nerdel (2017), these ways of thinking and working have a dual function: on the one hand, the understanding of important technical aspects should be ensured, and on the other hand, methodological skills should be acquired. When choosing specific scientific ways of thinking and working for the project, we are guided by Steffensky's description (Steffensky, 2018): Asking questions, hypothesising, measuring, planning and conducting investigations, observing, comparing, ordering, classifying, analysing and interpreting data, drawing conclusions, generalising, arguing, using models, and documenting.

To understand scientific ways of thinking and working, it is helpful to adopt an inquiry-based learning approach. Many aspects of research correspond to the aforementioned scientific ways of thinking and working, which are brought together in an inquiry-based learning process, actively experienced by the pupils.

Through inquiry-based learning, it is possible to develop skills that are required under the keyword 21st Century Skills (National Research Council, 2012) in the primary school curriculum. These skills include asking a question, investigating this question creatively and collaboratively using suitable methods, observing, experimenting, collecting data and drawing conclusions in order to answer the question posed at the beginning. All of these skills are part of inquiry-based learning but can also be practiced individually under certain circumstances (NGSS Lead States, 2013). Depending on the question, different scientific ways of thinking and working can be used and promoted.

If inquiry-based learning is implemented in the classroom, this can take place with varying degrees of openness (levels 0 to 3, see table 1) (Blanchard et al., 2010). The FoPs project materials were developed at levels 0, 1 and 2, enabling work to be carried out at different levels based on the same research question.

Table 1: Levels of inquiry (Blanchard et al., 2010, p. 581).

	Source of the Question	Data collection Methods	Interpretation of Results
Level 0: Verification	Given by teacher	Given by teacher	Given by teacher
Level 1: Structured	Given by teacher	Given by teacher	**Open to student**
Level 2: Guided	Given by teacher	**Open to student**	**Open to student**
Level 3: Open	**Open to student**	**Open to student**	**Open to student**

When implementing scientific ways of thinking and working, spoken and/or written language is essential. Children need to be able to put their thoughts, questions and arguments into words to be able to successfully discuss them with others. Many learners find this difficult. Appropriate scaffolding is therefore important to promote the transition to academic language and terminology in subject lessons through language-sensitive subject teaching (Gabler et al., 2020; Leisen, 2013; Lembens & Krebs, 2025; Quehl & Trapp, 2015) and also to enable participation with regard to highly diverse school classes.

The Materials In The Project

“The soup”, “The snow” or “My classroom” are some of the learning opportunities designed as part of the FoPs project. The subject is always a concrete matter that is physically available in the pupils' immediate environment. Dealing with it provides many opportunities to familiarise with and apply scientific ways of thinking and working in the classroom. When creating the learning opportunities, care was taken to ensure that a multi-perspective approach is possible, as required by the curriculum for general studies (BMBWF, 2023, p. 1). This makes it possible to link the areas of competence (social science, natural science, geography, technology, history and economics) in a structured, meaningful and appropriate way when dealing with the content.

Extensive materials for teachers and students are available for each topic. Meaningful symbols have been used in the text for better orientation and easier readability. In order to provide teachers with the best possible support for their lesson planning, the teachers’ guide contains the following elements: a brief description of the respective matter, a detailed presentation of the individual investigation sheets with a description of the scientific thinking and working methods to be practiced, the levels of inquiry-based learning and the required materials for the investigations, a list of possible links to all areas of competence in science teaching, and ideas for the solution of the students’ investigation sheets. The explanation of the content is provided at different levels of difficulty, one for teachers and one for pupils.

The investigation sheets for pupils are differentiated and named as follows: A) Sheet for all researchers (the basic exploration of the matter using all senses); B) Sheet for beginning researchers is based on level 1 of inquiry-based learning (Both research questions and concrete suggestions for carrying out scientific investigations are provided on the sheet and are worked on by pupils.); C) Sheet for advanced researchers is based on level 2 of inquiry-based learning (Research questions are formulated, the planning and execution of the scientific investigations as well as the interpretation of the observations or collected data are the responsibility of the pupils.).

Research Design

In addition to a classic evaluation design which we used to further develop the materials, we wanted to think ahead. We were interested in learning what features concerning learning materials teachers and pre-service teachers expect so they use materials repeatedly even after the project period ended. Therefore, the research questions of the study presented here are: What is necessary for teachers to integrate our materials into their lessons in the long term? What are their wishes for the provided materials? To what extent do the materials meet their requirements?

To answer these questions, a questionnaire consisting of five sequences was conducted (Baur & Blasius, 2019). A four-level Likert-scale was used, ranging from “very important” to “not important at all”. The first part is about the importance of different aspects of the subject “scientific studies” like perceived importance of inquiry-based learning or nature of science. The second part addresses the preparation of lessons. Sample items are “The time required for preparation is minimal.”, “There is easy access to the materials.” or “The additional consumables (glasses, pens, …) for the investigations are easily available.” The third part shifts the focus to the pupils with statements like “The pupils have fun with the materials.”, “Accessibility for all pupils (screen reader, colors, design) is given.” or “Linguistic differentiation is possible with the materials.” The focus of the fourth part is on the teachers’ guide with the following items: “The desired competencies of the pupils are specified.”, “Lesson plans are available.” or “Suggestions for possible solutions are given.” The final section deals with the alignment of the pre-service teachers' ideas with the materials from the FoPs project.

40 pre-service teachers on the Bachelor's degree program in Primary Education (7 male, 33 female, 0 diverse) completed the questionnaire. The participants' progress in their studies varied greatly. 21 were in the 3rd semester, 12 were in the 7th semester. The remaining seven pre-service teachers were in their 5th to 9th semester. 17 of the 40 pre-service teachers are currently teaching part-time in a primary school, two even full-time.

Findings

This section presents the answers of the pre-service teachers, beginning with an evaluation of the importance of different aspects of the subject "general studies" (see figure 1). The most important aspect is the importance of natural sciences in everyday life, followed by inquiry-based learning and that the students conduct experiments. In general, the pre-service teachers consider most of the aspects to be important. Only the aspect of "talking about how natural scientists work", which is one of the aspects of nature of science, is considered less important. In Austria, it seems that this topic is still not given the attention it deserves.

Figure 1. How important are the following aspects of the subject?

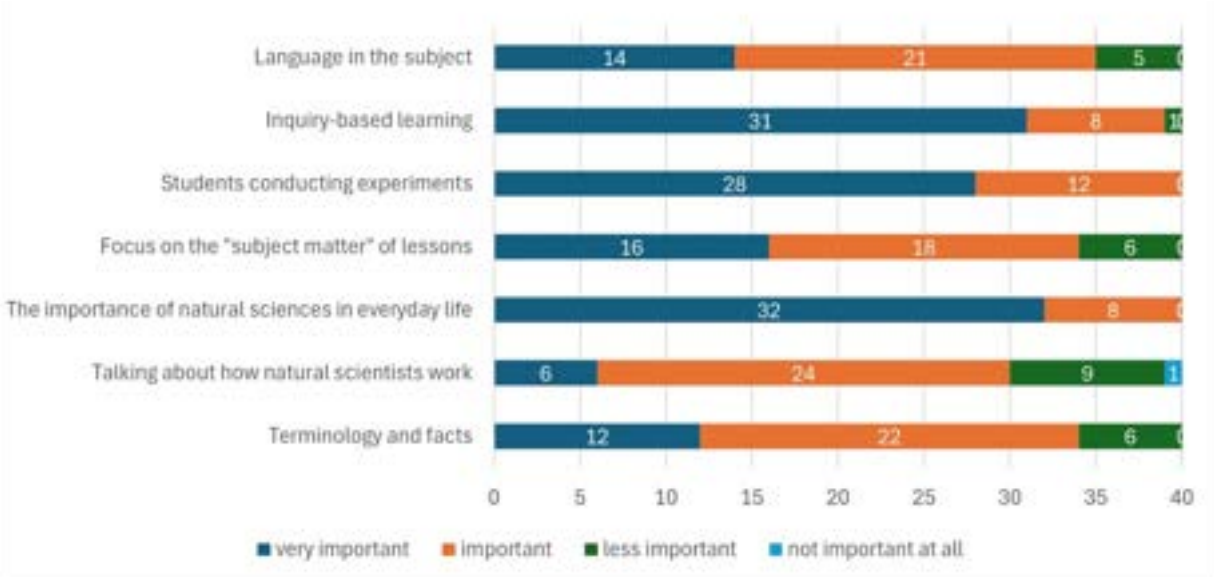


Figure 2 shows relevant criteria concerning pupils with interesting results. While hands-on and minds-on parts are quite important, the item with the highest priority for the pre-service teachers is that the pupils have fun (all 40 pre-service teachers consider it to be either very important or important). Another important criterion is the possibility of internal differentiation in terms of content. 24 pre-service teachers say that it is very important and 15 say that it is important.

The importance of aspects of language was evaluated using two items. Linguistic differentiation is only slightly important (very important: 18), the easy understanding of texts is much more important (very important: 26).

For the pre-service teachers it is important that the pupils can work independently (very important: 23) and that there is a clear and easy-to-understand structure (very important: 26).

Another part of the questionnaire is about the teachers' preparation for the lessons. Figure 3 shows the priorities of the pre-service teachers. The items ranked as "very important" according to the response options are that the materials are easily adoptable and accessible, followed by a digital availability. Interestingly, 26 pre-service teachers stated, that it is "less" or "not important" if additional work like cutting out or crafting is necessary. Only 10 out of the 40 pre-service teachers said that a minimal preparation time is "very important".

Figure 2. How important are the following criteria concerning students?

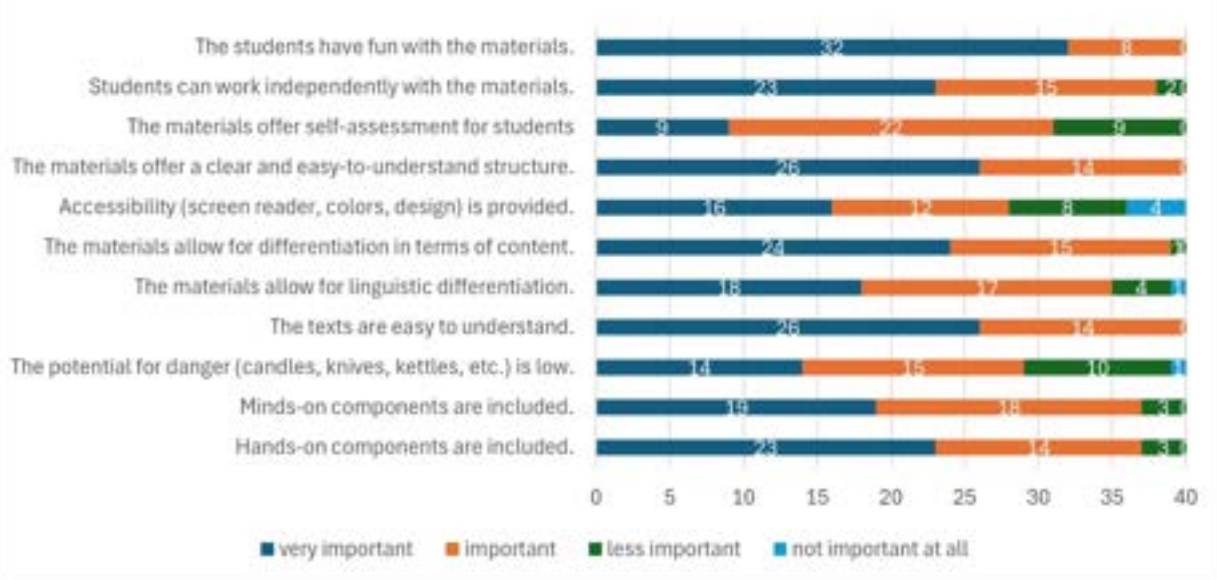


Figure 3. Preparation of lessons

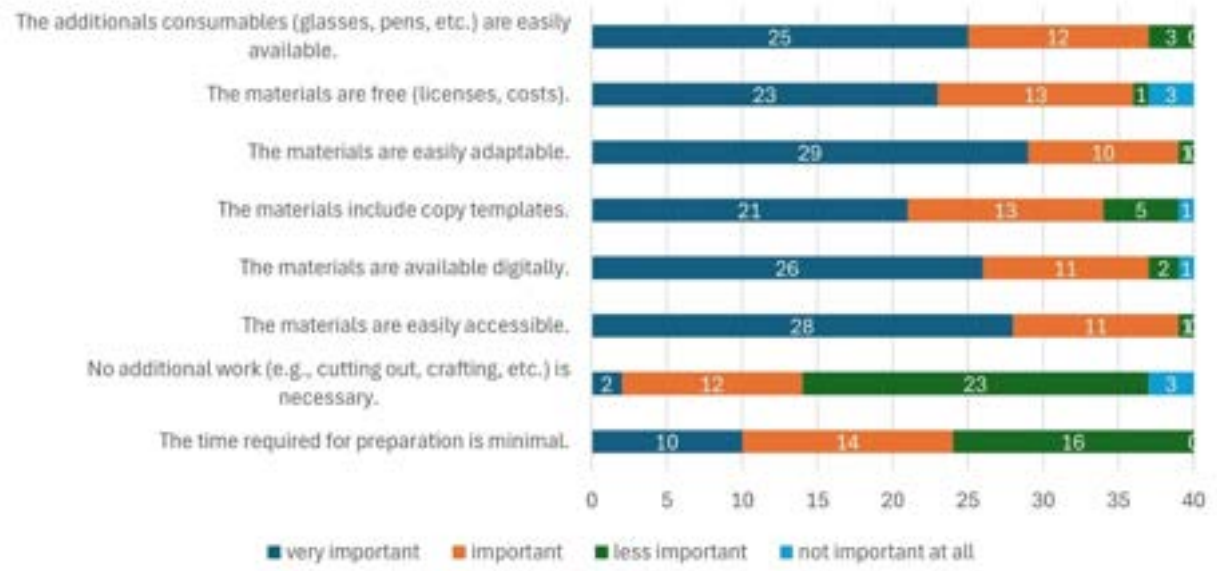


Figure 4 illustrates the fit between the pre-service teachers' expectations and the project materials. It seems that the expectations have been well met. The lowest level of acceptance was shown concerning the preparation.

At the end of the questionnaire, the teachers' students had the option to write a comment. There, comments like "Cool idea, I'd definitely try that out in class!" but also "The presentation seems a bit monotonous/boring." could be found. The comments were varied, but not helpful in terms of further development.

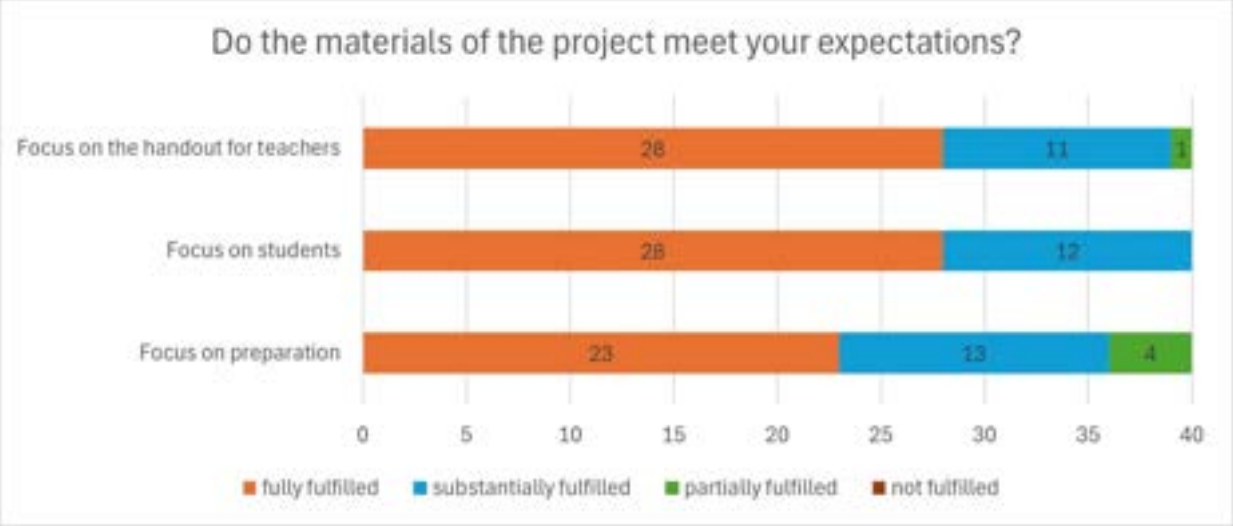
Discussion

In this paper, we presented the findings from a questionnaire completed by pre-service teachers.

The aim of our project was to create materials that are used even after the project is finished. To learn more about the features the materials need to have, a questionnaire was conducted.

The pre-service teachers have very different expectations. It is impossible to meet them all at the same time. Therefore, some compromises must be made between the following three juxtapositions.

Figure 4. Do the materials of the project meet your expectations?



Short information vs. exact description: One point that was raised in the open section of the questionnaire was the amount of text in the teachers' guide that had to be read. The desire for shortening and simplification is understandable. However, the problem with this is that something always gets lost when things are shortened. This contradicts the goal of carrying out the teaching as intended.

Easy adaptability vs. intended structure: It is great that pre-service teachers are willing to invest time for adaptation to the respective learning groups. To enable them to meet the needs of their pupils, it would be desirable to provide an easily modifiable format. However, the worksheets are based on findings from the literature and have been evaluated before dissemination. Therefore, revising the worksheets is not always desirable from the authors' perspective.

Student-oriented vs. scientific-oriented: The questionnaire revealed that pre-service teachers tend to prioritise simplification and children's enjoyment. They focus mainly on the children and their experiences when planning lessons and teaching. Content and scientific concepts play a minor role. This approach disadvantages children from educationally disadvantaged backgrounds (Fölling-Albers, 2022). The project materials are intended to support the currently required addition of a science orientation to the curriculum.

However, there are some questions open. It is still unclear what motivates (pre-service) teachers to engage more intensively or in greater detail with the materials. How long do teachers need to decide for or against this? In any case, the successful combination of professional development courses with the distribution of materials can be relied upon (Lipowsky & Rzejak, 2021).

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Exploring Science Through Screens: An Analysis Of Mobile Apps For Preschoolers

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Mobile applications are becoming an increasingly common part of the everyday experience of preschool children, including their encounters with science-related content. However, the pedagogical structure of these digital environments has not yet been adequately examined. This study explores how scientific content is presented in mobile apps designed for early childhood education. A qualitative content analysis was conducted on 14 science-themed apps, which were selected through a systematic search of the Apple App Store and Google Play Store between December 2024 and January 2025. The analysis focused on five dimensions: Scientific content; pedagogical appropriateness; motivation; inclusivity; and science communication. The findings suggest that life science themes (e.g. plants, animals and life cycles) are more prevalent than physical or earth science topics. Applications commonly include visually rich, reward-based interaction patterns that may help to sustain engagement. However, explicit conceptual explanations, scaffolded guidance and opportunities for dialogic or inquiry-based interaction are limited within the apps themselves. Feedback structures generally focus on task completion rather than reasoning processes. Inclusive representations are present in some cases, but not systematically. Overall, the apps appear to provide exposure to scientific phenomena, while features associated with deeper conceptual support are less visible. This study provides a descriptive overview of current design trends and could inform future research and development efforts aimed at enhancing the pedagogical quality of digital science experiences in early childhood.

Keywords: Early Childhood Science; Educational Apps; Mobile Learning; Science Communication; Preschool STEM

Introduction

Young children are inherently curious, driven by an intrinsic desire to explore and make sense of the world around them (Jirout & Klahr, 2012). Research characterizes preschoolers as little scientists who actively seek to understand biological and physical phenomena through observation and explanation (Gopnik, 2012; Zimmerman, 2007). From early childhood, children display sustained interest in how nature works, positioning science as a particularly meaningful domain within early education (French, 2004). Engagement with scientific content can further stimulate this curiosity. Studies indicate that exposure to science topics increases children's motivation to learn and supports the development of scientific vocabulary and discourse (Oppermann et al., 2018; Peterson & French, 2008). With digital technologies becoming an integral part of life today, mobile applications offered on smartphones and tablets are among the primary environments where children can interact with science.

In contemporary childhood, digital technologies—particularly mobile applications on tablets and smartphones—have become prominent environments where children encounter scientific ideas. The National Association for the Education of Young Children emphasizes that technology and interactive media can be valuable learning tools when used intentionally and in developmentally appropriate ways (NAEYC & Fred Rogers Center, 2012). Empirical studies support this position, showing that well-designed digital experiences can positively influence learning outcomes in early childhood (Bullock et al., 2017; Xie et al., 2018). Touchscreen educational apps, for instance, have produced meaningful gains in early literacy and mathematics (Griffith et al., 2020; Outhwaite et al., 2022). Within science education specifically, research demonstrates that

preschoolers can learn new factual information through interactive apps as effectively as through direct instruction (Kwok et al., 2016) and that mobile game contexts can support understanding of physical science concepts such as projectile motion (Herodotou, 2018). These findings suggest that thoughtfully designed science apps have the potential to enhance conceptual learning and scientific understanding during early childhood.

Contemporary evidence suggests that pre-school children spend around 2–3 hours a day on screen-based activities (Chang et al., 2018; McNeill et al., 2019), devoting almost an hour of this time to using mobile apps (Rideout & Robb, 2020). This level of exposure highlights the important role that app design plays in shaping early learning environments. When used in supportive contexts, educational technology can meaningfully contribute to early childhood development and learning (Clements et al., 2024). Consequently, the pedagogical quality of mobile applications, particularly those accessed via tablets and smartphones, becomes a central concern in early education research. Despite this extensive engagement, there is limited systematic knowledge about the scientific content that children encounter in mobile apps. In Turkey, there is a notable absence of comprehensive analyses examining the science-related content of children's mobile applications. A recent study evaluating STEM-oriented mobile apps (Konca et al., 2024) found that most of the apps were in English and that evaluations focused primarily on general app features rather than the scientific content, conceptual accuracy or science communication practices. Consequently, our understanding of how science is represented, structured and communicated in digital environments frequently accessed by young children is inadequate. A comprehensive examination of the scientific content embedded in preschool mobile apps is therefore necessary. Such analyses could shed light on the current state of digital science learning environments and provide a foundation of evidence to guide parents, educators, and developers in creating developmentally meaningful and pedagogically sound early science experiences.

Method

This study employed qualitative content analysis to examine mobile applications designed for preschool children (aged 3–6) that contain science-related content. A systematic search of the Apple App Store (iOS) and Google Play Store (Android) was conducted between December 2024 and January 2025. Search terms included science, ages 3–6, preschool, early childhood, and popular. Additional scans were conducted within the Education and Kids categories, and the most downloaded and highest-rated children's applications were examined. The search and selection procedures were documented to ensure transparency and reproducibility of the sampling process.

Applications were included if they explicitly contained scientific content (e.g. topics related to life sciences, physics, or earth sciences) and targeted an early childhood audience. Applications that focused solely on general early learning without science-related components were excluded. Based on these criteria, 20 applications met the initial inclusion threshold. The sample included both free and paid applications that were widely used by children in Turkey, ensuring that the analysed content resembled real-life usage contexts. Although 20 applications met the initial search criteria, a secondary eligibility screening was conducted during the coding phase to ensure that apps contained accessible science content relevant to preschool learners. Applications in which science-related sections were locked behind paywalls, lacked substantive science content despite categorical labeling, or targeted broader age ranges without developmentally appropriate science activities were excluded from full analysis. Following this refinement, 14 applications constituted the final analytical sample. This step enhanced the ecological validity of the content analysis by ensuring that findings reflected children's actual exposure to science-related

experiences within apps. Table 1 presents the final set of applications included in the analysis, along with their primary science domain classifications.

Table 1. Primary dcience domains represented in the analysed preschool science apps.

App Name	Primary Science Domain
MarcoPolo Weather	Earth Science (weather, seasons, atmosphere)
TRT Çocuk Anaokulum	Mixed (plants, animals, environment)
Sevimli Dostlar	Life Science (animals, plant growth, health themes)
What's in the Ocean	Life Science (marine life, ecosystems, food chains)
Caillou	Life Science (living–nonliving, plant/animal care)
TRT Çocuk Oyun Dünyası	Mixed (plant growth activities)
Farm Games for Kids	Life Science (farming, animals, food sources)
Animal Farm for Kids	Life Science (farm animals, habitats)
Minikler için Eğitici Oyunlar	Life Science (animals, plants)
Playo	Mixed (nature, weather, environmental elements)
Maşa ile Koca Ayı	Life Science (farming, animals, plant growth)
Eşle ve Öğren	Life Science (animals, plants)
TRT Kare	Mixed (day–night, hot–cold)
Science Games	Mixed (life cycles, states of matter, space themes)

The coding framework followed a conventional qualitative content analysis approach as described by Hsieh and Shannon (2005). Rather than applying a predefined coding scheme, codes emerged through repeated interaction with the apps, enabling patterns specific to preschool science applications to be identified. At the same time, existing academic work in early childhood education and digital learning provided theoretical guidance without constraining interpretation (e.g. Bruner & Kúcelová, 2024; Callaghan & Reich, 2018; Clements et al., 2024). This approach ensured that the analysis remained data-driven while aligned with existing research on educational media and early science learning. The coding framework consisted of five categories: Scientific Content, Pedagogical Suitability, Motivation, Inclusivity, and Science Communication. Subcodes addressed conceptual accuracy, misconceptions, scaffolding, reward structures, diverse representation, accessibility, and communication models.

The analysis was conducted by two coders. The primary coder engaged with each application for approximately 15–20 minutes, systematically documenting interface structure, task flow, and science-related content. Code definitions were subsequently refined. The second coder was trained on the framework, and both coders jointly coded five pilot applications to calibrate code application. The second coder then independently coded 30% of the sample. Disagreements were discussed and resolved, resulting in a final coding scheme with explicit definitions. Inter-coder reliability was high (Cohen's $\kappa = .94$). Analytical notes were used to identify cross-case patterns.

This study involved analysing publicly accessible digital applications and did not include human participants, personal data or identifiable user information. Accordingly, formal ethical approval and informed consent procedures were not required in accordance with institutional research ethics guidelines.

Results

The results are organized according to the five analytical dimensions guiding the coding framework: Scientific Content, Pedagogical Appropriateness, Motivation, Inclusivity, and Science Communication.

Scientific Content

The analysed applications were dominated by life sciences content. Most of the applications focused on biological and nature-related themes, such as plants, animals and health. Gardening simulations were popular, involving children planting seeds and watering the soil, before observing fruits or vegetables appear almost instantly, sometimes after just one interaction. Despite these accelerated representations, some applications presented scientifically accurate concepts. For instance, the app depicted in Figure 1 accurately positioned roots and shoots to depict plant growth, correctly representing both underground and above-ground structures. Animal themes were also prevalent, ranging from farm animals to insects. Many applications included repetitive sequences, such as life cycles or the stages of vegetable cultivation. Figure 2 illustrates the human life cycle, and the same application presents the life cycles of butterflies and frogs, visually highlighting the differences between species. While these topics were consistent with children's familiarity with nature and living organisms, the limited diversity of disciplines was evident. Content related to physics and earth sciences was scarce, suggesting that the applications primarily focused on life sciences.

Figure 1.

Accurately positioned vegetables



Figure 2.

Human life cycle



Although the apps generally aimed to present accurate information, various forms of scientific inaccuracy were observed. A common pattern was the oversimplification of processes. In particular, instantaneous depictions of plant growth misrepresented the temporal dimension of biological development. Anthropomorphic representations were also frequent. For example, in one app a *queen bee* character appeared dressed in human clothing and behaved as a royal figure. Figure 3 shows a crowned cartoon bee character illustrating this type of representation.

Figure 3.

Anthropomorphic Bee Character



Figure 4.

Sunlight and Microorganism



Furthermore, some scientifically grounded phenomena were presented in a way that could lead to misunderstandings. In one app, for example, children were asked to hang out the washing and position it so that it would receive sunlight. The drying process was shown gradually. However, the underlying mechanism of heat transfer was not explicitly represented. In the same section, when the children zoomed in on the clothes, visual depictions of microorganisms appeared and then disappeared when the sunlight icons were shown (see Figure 4). Scientific literature indicates that sunlight can reduce the survival of pathogens and the risk of infection (Hobday & Dancer, 2013). In this section, relevant concepts were linked to observable outcomes, but cause-and-effect relationships were not explicitly defined. Consequently, the representations operated through surface-level causal framing rather than mechanistic explanation. Using sunlight icons as visual representations may evoke the idea of sunlight as tangible particles, which could lead to conceptual misunderstandings.

Pedagogical Appropriateness

Each app's design was examined in terms of its alignment with developmentally appropriate practices for preschoolers. The majority of apps maintained simple interfaces and instructions, minimizing text and relying primarily on visual elements, icons, and audio cues. These design features align with the early literacy levels typical of preschool children. However, the depth of learning observed across apps was generally limited. Built-in progression mechanisms that extend learning beyond basic task completion were scarce. Gradual increases in difficulty and the introduction of more complex concepts in later stages were rarely observed.

In most apps, the cognitive demand of tasks remained relatively constant, while different life science concepts were introduced across successive sections. The sequence of concepts appeared to move from topics likely to be more familiar to children (e.g., plant cultivation) toward less familiar domains (such as fishing, beekeeping, and sheep shearing). Later stages included more specific contextual concepts. For instance, one app presented a task requiring drainage of water accumulated around a cherry tree following rainfall. In this section, children were required to complete the action correctly before progressing. However, the concept of *drainage* was not explicitly named in text or speech; the process was presented solely as a task-based interaction. In such cases, concepts were embedded within activities but were not accompanied by explicit conceptual labelling or integrated explanation.

Another dimension of pedagogical design concerns how apps guide children during learning. Educational applications for preschoolers are typically expected to provide scaffolding through hints, modelling, or feedback that supports learning from mistakes. Most apps in the sample adopted a trial-and-error approach. Children could interact freely, correct actions were reinforced through positive feedback, whereas incorrect actions were typically addressed through brief auditory cues or simple redirection. Instances of explanatory feedback were not observed. This pattern indicates that opportunities for explicit conceptual clarification were limited within the apps' feedback structures.

Motivation

Consistent motivational design features were observed in all applications. One such feature was the widespread use of instant feedback systems. Almost all applications reinforced children's actions with lively sounds, animations and celebratory visual elements. Upon completing a task, stars, music or enthusiastic character reactions were often displayed on the screen to provide immediate reinforcement (see Figure 5). These feedback events occurred rapidly and at frequent intervals throughout interactions. Reward structures extended beyond symbolic indicators. Many apps incorporated progression-based systems that unlocked new content or virtual collectibles upon completing a level. Gamification elements such as points, badges and level advancement made progress visible within the app environment. Stars were particularly common as a performance marker, serving as a visual representation of achievement (see Figure 6).

The narrative framework and character design further supported interaction. Various activity formats and animated characters were widely used. Some apps featured well-known characters that children would recognise from YouTube, cartoons or books. This placed learning activities within familiar narrative contexts. In such cases, these characters served as guides or participants in science-related activities. Several applications featured adaptive pacing, where the transition speed or task flow changed based on the child's interaction speed. Although not common, these design models were present in multiple applications. Elements supporting autonomy were also present, allowing children to select activity centres within the application and choose between different characters or task paths.

Figure 5.

Instant celebratory feedback



Figure 6.

Star-based reward



Inclusivity

The inclusivity analysis addressed both on-screen representation and accessibility for diverse users. In terms of representation, the diversity of characters and contexts was limited across most of the apps. Many featured animal protagonists or generic cartoon children without clearly identifiable racial or cultural backgrounds. When human characters were present, some degree of gender diversity was evident. However, only one app in the sample displayed more explicit inclusive representation. In this underwater exploration-themed app, the diver characters were portrayed as a girl and a boy. One character was depicted as a light-skinned boy and the other as a dark-skinned girl. The characters worked together and had equal roles in scientific exploration. In this example, both gender and ethnic diversity were visually represented. However, none of the apps addressed cultural dimensions of science, such as scientists from different parts of the world or references to traditional knowledge systems. Notably, there were no characters with visible disabilities. There were no depictions of mobility aids or assistive devices, nor any scenarios reflecting differently abled individuals. Overall, these preschool science apps appeared to depict a relatively homogeneous landscape, largely reflecting able-bodied and Western-oriented contexts.

Science Communication

The apps were examined to see how scientific information was presented, and whether children were encouraged to engage in scientific reasoning or dialogue. Overall, the apps were found to follow a one-way 'show-and-tell' approach, which is consistent with a deficit model of science communication. Information or outcomes were usually presented for the child to absorb, rather than encouraging active thinking or inquiry. For instance, in one app, when a child waters a virtual plant, the narration says, 'Let's water it so it can grow', accompanied by a watering icon. However, the child is not asked to consider how or why this process occurs. Although the communication format was embedded within interactive gameplay, it was largely scripted and instructional in nature. No dialogic communication model, in which children are asked open-ended questions or encouraged to express their ideas, was observed. Interactive elements such as reasoning-based multiple-choice prompts (e.g. 'Why do you think this happens?') were not present. A participatory communication model, in which children record observations, make predictions or freely explore and draw conclusions, only appeared in limited forms. Some apps included sandbox-style exploration areas where children could mix materials and observe the results. However, even in these cases, the apps did not provide scientific explanations for the phenomena observed.

Scientific content was predominantly conveyed through visual and animated representations. Processes such as seed germination were demonstrated through animation. However, these representations did not incorporate explanatory dialogue or conceptual justification. In summary, science communication in preschool science apps was characterised primarily by one-directional information delivery. While the apps focused on demonstrating phenomena, there were limited opportunities for interaction requiring questioning, explanation or verbalisation of ideas.

Discussion

The analysis of 14 preschool-oriented science applications indicates the presence of highly engaging yet pedagogically under-supported digital learning environments. The findings suggest that while these applications increase children’s access to scientific content, they remain limited in meeting core principles of early childhood science learning. One of the major strengths of the apps is accessibility. Consistent with research demonstrating that children can acquire scientific knowledge through interactive media (Kwok et al., 2016), the apps provide exposure to scientific concepts that children might not encounter before formal schooling. The predominance of life science themes reflects developers’ tendency to capitalize on young children’s natural interest in animals and plants. However, the limited representation of physical and earth sciences points to a narrow interdisciplinary scope. Early childhood science education aims for a balanced distribution of domains, including physical science concepts such as forces and materials (French, 2004). The current distribution may reinforce, for preschool children who spend extensive time with apps, the perception that science is primarily equivalent to nature.

The anthropomorphic representations and depictions of instantaneous biological processes observed in the apps raise pedagogical concerns regarding potential misconceptions. Anthropomorphic narratives can enhance engagement and may even foster positive attitudes toward animals (Reider & LoBue, 2024). However, Bonus and Mares (2019) demonstrated that preschool children’s ability to evaluate the reality status of information presented in educational videos is associated with learning and transfer, suggesting that distinguishing real from fictional elements may not be straightforward for young learners. In most of the apps analysed, this distinction was not explicitly clarified. This finding aligns with early childhood teachers’

concerns that anthropomorphism may contribute to cognitive confusion (Kallery & Psillos, 2004). Given that misconceptions acquired in early childhood can persist over time, clearer separation between anthropomorphic elements and scientific explanations becomes essential.

Motivational design features constitute one of the strongest aspects of these applications. Frequent rewards, gamified progression, and celebratory feedback mechanisms help sustain children's engagement. Positive emotional experiences with science in early childhood are known to support later motivation for science learning (Jirout & Klahr, 2012). Nevertheless, the intensive use of extrinsic rewards raises questions regarding depth of learning. In edutainment designs where game elements are appended as external rewards to learning elements (e.g., *the chocolate-covered broccoli* approach), attention and flow may shift from educational goals to game goals. Indeed, lower levels of learning-task engagement have been reported under extrinsic design conditions. In contrast, the intrinsic integration approach, in which learning content and game mechanics are structurally unified, enables motivation and cognitive engagement to align toward the same objectives, resulting in a more balanced learning experience (Habgood & Ainsworth, 2011).

Another critical limitation concerns feedback structures. While apps celebrate correct responses, they rarely explain why incorrect responses are wrong. Encouraging children to explain phenomena is known to strengthen conceptual understanding (Zimmerman, 2007). Transforming errors into explanatory learning opportunities could more effectively connect motivation with learning processes. Regarding inclusivity, the findings parallel broader trends in children's digital media. Although gender representation appeared relatively balanced, ethnic diversity and representations of disability were largely absent, aligning with research indicating limited diversity in preschool applications (Bruner & Kucirkova, 2024). The analysis also showed that characters were predominantly animals or humans. This may be coded as a potentially inclusive feature, as animal characters can serve as culturally neutral figures that transcend specific social identities (Williams, 2014).

The most prominent pedagogical gap emerged in the domain of science communication. The apps predominantly adopted one-directional information delivery. Phenomena were visually presented, yet opportunities for questioning, explanation, and dialogic interaction were limited. Early science education literature emphasizes that guided inquiry and conversational exchanges are critical for conceptual development (Peterson & French, 2008). The absence of such dialogic processes may result in these apps functioning more as visual information sources than as interactive learning tools.

Limitations and Implications

This study is based on a qualitative content analysis examining the pedagogical structure of science-focused mobile applications designed for the preschool age group, and therefore carries several limitations. First, the sample was limited to 14 applications selected through a systematic search conducted between December 2024 and January 2025 on the Apple App Store and Google Play Store. Given the dynamic nature of app ecosystems, rankings, visibility, and availability of applications may change over time. Accordingly, the findings represent a snapshot of popular content within a specific time frame. Second, the study did not include direct measurement of children's learning outcomes. Evaluations were grounded in expert interpretation of app content features, pedagogical design elements, and the early childhood science education literature. Therefore, the results offer inferences about the potential learning affordances of the applications but do not experimentally verify actual learning gains. Third, the analysis focused on the design characteristics of the applications, without examining how children and caregivers experience these apps in naturalistic use contexts. App engagement is shaped by multiple factors, including

adult guidance, duration of use, contextual support, and individual child characteristics. As such, discrepancies may exist between the pedagogical potential identified in the design and the learning experiences that occur in real-life usage.

Despite these limitations, the study provides important implications regarding current pedagogical tendencies in preschool science applications. The findings indicate that while digital designs are strong in motivational engagement, they remain underdeveloped in conceptual structuring, dialogic learning opportunities, and inclusive representation. This suggests a need for digital learning experiences to align more closely with established principles of effective early childhood science education.

Finally, collaborations among researchers, app developers, and educators may enable research findings to more directly inform design processes. Such interdisciplinary approaches are critical for enhancing the pedagogical quality of digital science environments developed for early childhood learners.

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Creative Sparks And Constructive Tensions: How Resistance Shapes Young Children's Collaborative Engineering Design

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This study examines how young children demonstrate creativity during collaborative engineering design tasks in early childhood education. Using a basic qualitative approach, researchers observed 17 children (ages 4-7.5 years) engaged in engineering projects at a Montessori summer program. Analysis of conversations during a shelter design task revealed both conventional aspects of creativity (novelty, risk-taking, variety) and an unexpected element: resistance. Rather than impeding progress, instances of resistance—where children challenged each other's ideas—served as catalysts for creative development and solution refinement. Children's resistance fostered deeper engagement with design constraints and facilitated collaborative problem-solving. For example, when children resisted certain design choices, it led to more sophisticated considerations of material properties and physical concepts like light and shadow. These findings suggest that constructive resistance should be recognized as an integral component of creative development in early childhood engineering education, with implications for both research and practice in STEM education

Keywords: Early childhood education, engineering education, critical thinking

Introduction

Engineering education in early childhood has been increasingly recognized as a valuable component of young children's development, yet it remains relatively underexplored in both research and practice (Cunningham & Kelly, 2017). While much attention has been given to literacy and numeracy, the integration of engineering concepts in early education provides unique opportunities for fostering creativity and problem-solving skills among young learners. Early childhood engineering activities, such as building structures, designing simple machines, or experimenting with materials, allow children to explore the world around them in innovative ways, thus laying a foundation for later STEM learning (Moore et al., 2019). Despite this potential, the creative processes children engage in during these activities are often disregarded as valuable (Bolden et al., 2020). In this study resistance appears as an unanticipated analytic finding, emerging as a productive form of participation through which children challenged ideas, negotiated design decisions, and advanced creative engineering thinking.

Framework And Relevant Literature

Creativity is foundational to human development, extensively studied and valued in educational contexts (Rhodes, 1961). Contemporary research underscores it's vital role in fostering critical thinking, problem-solving, and innovation—abilities essential for navigating future complexities (Beghetto & Kaufman, 2017). Defined by divergent thinking, originality, flexibility, and the ability to generate novel solutions, creativity engages multiple brain networks and can be cultivated through intentional educational interventions (Runco, 2014). Notably, resistance, characterized as constructive challenges to ideas, enhances creativity by fostering reflection, idea refinement, and collaborative problem-solving. Pedagogical strategies promoting autonomy, exploration, risk-taking, and constructive resistance effectively nurture creativity across disciplines and educational levels (Beghetto & Kaufman, 2017).

In early childhood education, creativity holds significance as it aligns with young children's inherent tendencies toward imaginative play and exploration. These formative years of peak neural plasticity, provide an optimal period to cultivate creativity (Mohammed, 2018). Imaginative play and exploration underpin cognitive flexibility, problem-solving skills, and emotional regulation (Stoltz et al., 2015). Resistance, through questioning and rethinking, aligns with young learners' propensity to experiment with ideas, challenge peers, and refine their thinking. Play-based learning environments significantly shape creative development, with STEM education offering unique opportunities to integrate creativity. Activities in engineering design, scientific inquiry, and mathematical problem-solving not only require creative thinking but also foster deeper conceptual understanding, engagement, spatial reasoning, and knowledge retention (Stoltz et al., 2015).

Engineering tasks encourage young children to practice divergent thinking, while building critical and emotional skills necessary for future challenges (Moore et al., 2019). These activities support children's curiosity, adaptability, and resilience by prompting (Mohammed, 2018). Resistance plays a central role as children debate ideas, challenge designs, and refine solutions. For instance, questioning material choices or debating structural elements leads to deeper engagement and innovation. Understanding creativity in early childhood STEM education, including the role of resistance, equips educators to design inclusive, engaging experiences that foster creativity and prepare learners for lifelong innovation (Mohammed, 2018).

Creativity In Early Childhood STEM And Engineering Contexts

Creativity in early childhood is central to engagement in STEM and engineering education. Across the literature, creativity is consistently defined as the capacity to generate ideas that are both original and appropriate to the task at hand (Dow, 2022; Joubert, 2022; Peterson & French, 2021; Sternberg & Lubart, 1999). In STEM contexts, creativity manifests through problem-solving, experimentation, and iterative design processes that encourage young children to explore, question, and make sense of the world around them (Lippard et al., 2017; French, 2018).

Many argue that engineering design is a fertile context for fostering creative thinking in young learners. Studies have shown that when children are engaged in design challenges, they naturally exhibit engineering habits of mind like persistence, systems thinking, and creativity (Peterson, 2019; Lippard et al., 2017). This kind of thinking is nurtured through open-ended materials, child-directed inquiry, and opportunities for iteration (Murcia et al., 2022; Simoncini & Lasen, 2018). Creative markers in children's engineering and design work include novel uses of materials, original approaches to solving problems, and verbal or visual expressions that reflect children's reasoning and imagination (Tippett & Gonzalez, 2022; Kuhn et al., n.d.).

Resistance In Young Children's Engineering

Resistance in young children's collaborative group work and engineering activities can be both a site of tension and a source of generative potential. Resistance is not simply oppositional behaviour, but a legitimate form of agency wherein children assert their autonomy, question authority, and reshape their roles in learning environments (Rainio, 2008). Often emerging in social contexts where children encounter externally imposed structures or expectations, resistance shapes how children respond to such events as a teacher's vision for classroom norms or a group's idea of how a project should unfold. Rather than viewing resistance as defiance to be managed or eliminated, Rainio (2008) suggests that it can be a creative, transformative force. In the playworld studied, for example, a child's initial resistance evolved into meaningful participation once the activity allowed space for narrative flexibility and individual investment (Rainio, 2008). Similarly, Litvinaitė (2022) situates resistance within the broader context of cultural negotiation,

arguing that resistance can be a productive force that disrupts cultural reproduction and fosters hybrid ways of working and knowing. These insights align with sociocultural views that see agency as emergent from interaction, with resistance offering children opportunities to reconfigure the social and intellectual terms of engagement (Stetsenko & Ho, 2018; Vygotsky, 1978).

In the context of collaboration among young children, especially in early childhood engineering education, resistance may manifest as silence, withdrawal, refusal to follow peers' ideas, or challenging the assumptions embedded in others' proposals (Perumal, 2008; Rainio, 2008). The literature highlights how this behaviour is not necessarily unproductive. Instead, it signals that children are negotiating the norms of participation, authority, and identity within a group. Perumal (2008) emphasized that resistance in collaborative learning contexts often emerges as a response to the shift from passive reception to active engagement, particularly when students are asked to share cognitive or social authority. For young children in engineering tasks, this could look like questioning the utility of a peer's design, insisting on using an unconventional material, or rejecting a plan that doesn't align with their sense of how something should work. While these moments may appear disruptive, they can also prompt critical reflection, negotiation, and innovation within the group. Here, resistance is not a barrier to collaboration, it is a mode through which collaboration can be deepened and made more authentic.

Within early childhood engineering, resistance has particular affordances to advance thinking and design processes. Engineering design is inherently iterative, requiring testing, failure, and re-design (Cunningham & Kelly, 2017). When children resist a suggested solution or choose not to go along with a group consensus, they are engaging in critical evaluation and proposing alternative pathways. Litvinaitė (2022) describes how resistance can lead to greater creativity and the reconfiguration of roles and norms, allowing children to move beyond reproduction of adult-expected designs and toward genuine invention. Rainio (2008) and Perumal (2008) both argue that when children are given space to resist, new forms of agency and understanding emerge. In engineering tasks, this might include a child refusing to use an adult-suggested material because it does not meet the demands of their imagined function, or a child insisting that a tower's stability matters more than height. These actions reveal a depth of engagement with engineering concepts and an investment in the process that extends beyond compliance. Resistance serves as a catalyst for learning, identity development, and the cultivation of collaborative engineering mindsets.

Research Aim And Questions

The following question guided the study:

- How do young children demonstrate creativity when engaged in collaborative engineering design tasks?

Methodology And Research Methods

This study was conducted using a basic qualitative research approach, which allowed for close examination of how young children demonstrated creativity while engaging in collaborative engineering design tasks (Merriam, 2009). This methodology was well-suited to our focus on how children expressed themselves and made meaning through their talk, actions, and shared design experiences. Our goal was to better understand the character of children's creative participation during a summer engineering program. To do so, we analysed transcripts of audio recordings, design products, and interviews with participating children to explore their experiences with and expressions of creativity in engineering contexts (Merriam, 2009).

Context And Participants

The study took place over a five-day period during a summer enrichment program hosted by a public Montessori charter school located in a small community in the Mountain West region. This school, guided by Montessori principles such as hands-on learning, mixed-age classrooms, and learner-directed inquiry, offers year-round learning opportunities (Lillard, 2012, 2017). The summer programming retained these values, offering a flexible and supportive setting for continued exploration and play.

Twenty-four children were enrolled in the week-long program, although attendance varied by day. Participants ranged from nearly four years old to seven and a half years old, with the group comprising eight boys and sixteen girls. For engineering activities, students were grouped into teams of three or four by Montessori staff, who used their familiarity with the students' social skills and dynamics to create mixed-age, mixed-gender groupings.

Engineering Programming

The engineering curriculum used in the study was developed and facilitated by the research team rather than the classroom teachers, who remained in observational roles when present. A member of the research team with a strong background in early childhood and elementary teaching led the activities to ensure both developmental suitability and sound pedagogy. Each day began with a full-group session to introduce the engineering challenge, followed by group-based building and problem-solving. The engineering sessions ran for roughly three hours daily over the five-day period, giving children time to iterate on their designs, build social and collaborative skills, and interact with STEM ideas in tangible ways. The week's activities were adapted from the *Engineering is Elementary* (EiE) Kindergarten curriculum from the Museum of Science, Boston (Museum of Science, Boston, n.d.). The EiE curriculum supports young learners in exploring engineering through structured but age-appropriate tasks that emphasize the design cycle (Ask, Imagine, Plan, Create, Improve), real-world connections, and teamwork (Museum of Science, Boston, n.d.). These elements aligned naturally with Montessori educational goals, which value hands-on work, guided autonomy, and collaborative exploration (Cunningham & Lachapelle, 2014; Lillard, 2016). This alignment enabled smooth integration of engineering into an already inquiry-rich learning environment.

Two EiE units were selected and modified to shape the program: *Here's the Scoop: Designing Trash Collectors* (2018) and *Raise the Roof: Designing Shelters* (2018). The former served as an introduction to testing materials and iterative building in a fun, low-stakes activity. Later in the week, students tackled the shelter-building challenge, which was especially relevant due to a concurrent heat wave. This context helped students see how engineering could solve real-life problems and invited engagement with key scientific and design concepts like heat management, material properties, and structural integrity. The engineering curriculum was thoughtfully designed to root children's creativity in personally meaningful and relevant challenges.

Data Collection

Throughout the week, we audio-recorded all engineering sessions, including morning introductions, small-group work, and end-of-day reflections. Altogether, these recordings totaled over 18 hours. For this study, we concentrated our analysis on approximately six hours of audio captured during the small-group sessions of the *Raise the Roof* activity. This portion of the week's work was selected because it featured rich collaborative interactions, prolonged problem-solving efforts, and dynamic engagement with engineering practices. It provided a particularly strong window into children's creative and social participation.

Data Analysis

We focused our analysis on eight transcripts capturing children's dialogue and collaboration during the *Raise the Roof* engineering task, which asked them to design a sun shelter for a stuffed dog. All audio was transcribed verbatim to preserve the details of the children's language (Saldaña, 2016). We began with a deductive coding framework drawn from the OECD creativity rubric (OECD, n.d.) and the creativity domain of the engineering habits of mind framework (Lippard et al., 2019), both of which view creativity as a process. These initial codes are shown in Table 1.

To begin coding, each researcher individually analysed Transcript #1 using these predetermined codes while also engaging in open coding to allow for emergent insights (Strauss & Corbin, 1998). When we compared our initial codes, inconsistencies emerged, prompting a collaborative process of code refinement. Through discussion, we clarified and revised code definitions, resolved overlapping categories, and added new inductive codes (e.g., such as *resistance* and *uncertainty*) that captured additional nuances in the children's collaborative problem-solving (Charmaz, 2014; Patton, 2002; Strauss & Corbin, 1998).

We then recoded the first transcript using this revised codebook and assessed the alignment of our coding through axial coding techniques (Saldaña, 2016; Strauss & Corbin, 1998). This second round produced much greater consistency among team members. When discrepancies remained, we discussed them until consensus was reached. Using this finalized coding scheme, we independently analysed the remaining seven transcripts. Afterward, we met again to compare our coding results and resolve any further disagreements (Miles et al., 2014; Saldaña, 2016).

Following this final round of coding, we reviewed all coded excerpts and annotated them with interpretations about how they contributed to the unfolding creativity of the design process. This interpretive step helped us identify the ways specific moments and decisions advanced the children's learning and innovation (Braun & Clarke, 2006). We then grouped data by code and examined how themes intersected across categories. Through ongoing collaborative discussion, we refined these cross-code patterns to generate consistent, well-supported themes in our final analysis (MacQueen et al., 1998; Saldaña, 2016).

Results

Across our analysis of the children's dialogue during the engineering task, as they designed and constructed a shelter to keep a dog cool in the sun, we observed the presence of creativity aligned with expected markers. Children generated a variety of novel ideas (coded as *variety* and *novel*), often building on or combining others' contributions in flexible and exploratory ways. They demonstrated risk-taking behaviours, particularly when sharing uncertain or unconventional suggestions (coded as *risk*), and frequently introduced radically new ideas that shifted their group's design trajectory entirely (coded as *radical*). In many instances, children's ideas were grounded in scientific disciplinary knowledge (coded as *connected*), such as reasoning about heat absorption, material properties, or the relationship between structure and function. These connections not only enriched their design justifications but also highlighted how disciplinary thinking supported creativity during engineering. Table 1 (next page) gives examples of each of these markers of creativity, how they surfaced in the data, and how they shaped the engineering design.

In addition to the more expected markers of creativity, a new and unexpected theme emerged during our coding and analysis process – *resistance*. While not initially framed as a tenet of creativity in the literature, resistance surfaced as a meaningful form of participation and marker of young children's creativity when engaged in engineering. At times, children pushed back on

each other's suggestions, on design directions, or on the pace of decision-making. Rather than halting progress, this resistance often served to sharpen the group's thinking, slow the rush to consensus, and open space for further elaboration or clarification. In this way, resistance appeared not as a barrier, but as a generative force in the collaborative creative process, shaping how and when new ideas were taken up and how designs evolved.

Table 1. Markers of creativity, examples from the data, and descriptions of how the engineering design was shaped.

Marker of Creativity	Children's Quote from the Data	How the Process was Shaped
Variety	We could put it in the middle and one of us could wrap the tape around to make it stay (Child 14)	Adding on to an existing idea and design choice, pushing the process forward
Novelty	How about we make a circle, a door… (Child 2)	Proposes a new idea to the group, shifting the design ideas and process
Connected	That's, that's, is that skin? (Child 5)	Links knowledge about skin to properties of materials to enable materials choices
Risk	And we, and we might use that (Child 8)	Proses a new material, previously untested and undiscussed, pausing the group to weigh options
Radical	Why the middle? How would it get in the middle? We could just do it on the side and make it cute (Child 1)	Questions the design idea and suggests a change, changing the direction of the original design

We interpreted moments of resistance as instances of critical collaboration, or points in the design process when the children actively contested ideas. These expressions, which were sometimes subtle and occurred less often than other, more prominent themes, reflected important dimensions of creative agency. Rather than simply obstructing progress, children's resistance shaped the course of group decision-making and design development. Children voiced disagreement through short statements (e.g., "No," or "I don't think that will work") to pause the activity, to prompt reconsideration, or questioned material selections, placements, or strategies based. In some cases, doubt was articulated through reasoning tied to prior knowledge or lived experience. The excerpt below illustrates how resistance functioned as a productive and generative part of the engineering process:

Child 5:	Where is the other piece? The other part you wanted to put here?	
Child 6:	I've got a shadow!	*Connected*
Child 5:	No.	*Resistance*
	I don't think that will work	*Resistance*

	this side can't go here	
	it has to be all the way down to the ground	*Novelty*
Child 6:	Careful	*Connected*
	we almost made Penny hot	
Child 4:	To get in there	
Child 6:	We need shadows for Penny	*Connected*
Child 7:	Not yet	*Resistance*
	not there	
Child 6:	[Child 2] what do we do now?	
Child 5:	Okay, sir	*Novelty*
	What about this?	
	Use this?	
Child 6:	AHHHHH!	
	Yes.	
	That would be a good choice	

Resistance was purposeful. This is highlighted by Child 7 saying, "Not yet", implying a thoughtful response that indicated the proposed action did not align with the current stage of their process. Resistance did not derail the project or the design choices, it helped children refine their ideas. Some instances of resistance, like in the excerpt above, prompted shifts in direction of ideas and work, drawing the group's attention toward alternative possibilities. In other cases, work briefly paused as children explored alternative lines of reasoning or tried new possibilities. For example, when Child 6 said "No. Guys, hold on. This right here, do this…" the design process and engineering were paused to entertain a new idea. Only a few times did the resistance move the project seemingly backwards. In these cases, the resistance was purposeful action to undo a decision or take an idea apart. This was illustrated by Child 1 when they said, "Wait, stop, stop. We can't do that. We could take that apart…" Even actions that appeared to reverse progress (e.g., dismantling part of the structure) functioned as intentional moves toward refinement and improvement.

Resistance created tension which, in turn, sometimes sparkled deliberation. Although these moments slowed the immediate flow of activity, they also gave rise to new understandings or revised ideas. These actions did not impeded creativity; instead, they revealed children's active, critical engagement with both the design task and their peers. Rather than just complying with peer suggestions, children actively shaped how the work unfolded. Such forms of resistance and critical collaboration are overlooked in interpretations of young children's design activity. Through these interactions, children positioned themselves as evaluators and decision-makers who actively shaped the direction of the design work. Productive design work, in these cases, involved not only proposing ideas but also weighing alternatives. Design progress depended om moments when children collectively interrogated, reshaped, or set aside prior ideas. This positioned critical creativity as a driving force in the engineering process.

Discussion

When viewed through a sociocultural lens of resistance, the findings from this study position resistance as a meaningful and productive form of participation for young children in collaborative engineering design (Rainio, 2008). Rather than functioning as defiance or disruption, resistance emerged as an interactional resource for children as they questioned their peers' suggestions, delayed decisions, rejected other's proposed solutions, and engaged in practices central to engineering, including evaluating constraints, testing assumptions, and reconsidering how materials and structures function (Cunningham & Kelly, 2017). In this way, resistance became a visible mechanism through which the young children exercised agency within the group, shaping both the social and intellectual trajectory of the process (Litvinaitė, 2022).

Resistance was closely tied to several engineering habits of mind (Lillard et al., 2019), particularly creativity, optimism, and systems thinking. When the children resisted an idea (i.e., saying "not yet", pausing construction, proposing to take something apart) they often did so in response to perceived misalignments between a design choice and the problem at hand. These moments required the children to hold the design goal in mind, anticipate consequences, and advocate for alternatives that were more functional or aesthetically pleasing – practices that align with iterative and evaluative dimensions of engineering thinking (Cunningham & Kelly, 2017; Moore et al., 2018). Rather than completely halting progress, resistance slowed the pace of work in productive ways – creating space for deliberation, justification, and new ideas or thinking (Perumal, 2008). In these cases, resistance functioned as a form of collective sensemaking, enabling children to cooperate on thoughtful and intentional design choices.

Resistance also shaped the social dynamics of collaboration. Moments of pushback redistributed authority within groups, positioning children as both idea generators and as evaluators and co-directors of the design work. This aligns with the literature that conceptualizes resistance as a site for the negotiation of norms and where participation can be redefined (Perumal, 2008; Rainio, 2008). In early childhood engineering contexts, this kind of negotiation can support deeper engagement with both peers and materials. In turn, this allows young children to assert their perspectives, test boundaries, and contribute to shared and co-created solutions (Stetsenko & Ho, 2018).

Conclusion

This study contributes to early childhood engineering education by reframing resistance as an integral component of creative and collaborative design work. By attending closely to young children's talk during an engineering task, we highlighted how resistance can generate productive tension that has the ability to advance reasoning, support engineering habits of mind and ways of thinking, and deepen collective problem-solving and sensemaking. Moments of disagreement, hesitation, or pushback in young children's collaborative work do not always signal disengagement and conflict. Instead, these can be moments of engagement and possibility. Creating learning environments that allow space for children to exercise resistance by questioning ideas, slowing decisions, or revising plans, may support more authentic engineering practices and honour children as capable, thoughtful contributors to shared work. Attending more closely to resistance opens new possibilities for theorizing creativity in early childhood engineering as a socially negotiated process shaped by tension, critique, and collective decision-making.

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Learning The 5Rs To Promote Citizen Science In Primary Schools

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This study presents the development and validation of a Waste Manual based on the 5Rs (Reduce, Redistribute, Reuse, Recycle, Recover), designed to promote citizen science in primary education. The Manual integrates community involvement by offering a practical guide for teachers, parents, and guardians to foster environmental awareness and critical thinking in students. Aligned with Montessori principles, it emphasizes autonomy and active learning, encouraging students to develop skills for responsible decision-making. By engaging in structured activities, children learn to understand the environmental, social, and personal impact of waste management practices, fostering both individual responsibility and collective action. The pedagogical approach of the Manual incorporates levels of mastery adapted from Miller's framework, guiding students through progressively complex tasks that build their competence in applying the 5Rs. These activities also align with Bruner's spiral curriculum, ensuring that concepts are revisited and expanded upon to deepen understanding. The Manual encourages critical and creative thinking as central components for developing scientific literacy and fostering a long-term commitment to sustainable behaviours. The validation process involved eight experienced educators, each with advanced degrees and extensive teaching backgrounds, who analysed the Manual using a detailed questionnaire. Early results indicated its effectiveness in enhancing students' grasp of the 5Rs while also supporting their intellectual autonomy. Teachers highlighted the Manual's practical design, relevance, and potential to transform science education by linking theory with real-world environmental challenges. This paper explores the design process, the theoretical underpinnings, and the implications for advancing citizen science and sustainability education in primary schools.

Keywords: Citizen science, urban solid waste, Montessori.

Introduction

Primary education curricula highlight the importance of fostering environmental awareness and critical thinking. Despite differing approaches, they share the goal of equipping children with the skills to understand their environment and reflect on their actions, aligning with the broader aim of cultivating informed and responsible citizens.

This study addresses the integration of environmental education into primary schools through citizen science as a pedagogical framework. Specifically, it examines how the 5Rs (Reduce, Redistribute, Reuse, Recycle, Recover) can develop competencies in sustainable waste management and scientific literacy. The guiding research question is: How can we foster critical and active citizen science in primary school students? To explore this, a Waste Manual was developed to help teachers, parents, and guardians facilitate engaging activities centred on the 5Rs.

The Manual combines critical thinking principles, adapted from Miller's framework, with Montessori pedagogy, emphasizing autonomy and hands-on learning.

It aims to teach students the environmental impacts of waste while empowering them to take informed actions. By integrating theory with practice, the Manual seeks to instill lifelong habits of responsibility and scientific inquiry. This paper outlines the Manual's development, its activities, and validation by expert educators, demonstrating its potential as a transformative educational tool.

The Montessori Methodology For Citizen Science Learning

The Montessori methodology provides a robust framework for fostering critical thinking and active learning, essential for developing scientific literacy and promoting citizen science. This approach emphasizes hands-on experiences and autonomy, encouraging children to explore, experiment, and reflect meaningfully on their actions. Central to this framework is the concept that mistakes are opportunities for growth, fostering self-esteem, confidence, and intellectual autonomy—key for addressing complex environmental challenges.

Citizen science within the 5Rs framework requires students to acquire scientific knowledge and apply it to real-world scenarios. Montessori pedagogy supports this by offering authentic learning experiences that connect students with their immediate environment. Research highlights that grounding education in tangible, local experiences enhance understanding, retention, and a sense of responsibility toward sustainability (Reis, 2021; Kowasch et al., 2021; García, Reis, Vásquez, 2022).

By integrating Montessori principles, the 5Rs Waste Manual empowers students to progressively develop critical thinking skills, aligned with levels of mastery adapted from Miller's framework. Structured activities foster observation, analysis, and reflection, deepening students' understanding of waste management and its societal implications. This holistic approach equips students to act responsibly within their communities and contributes to broader environmental and scientific initiatives.

Mastering The 5Rs In Primary Education

Developing competencies for solid waste management requires a progressive approach, especially in primary education. The 5Rs provide a framework aligned with Miller's levels of mastery (1990), adapted by Albareda et al. (2019). As shown in **Table 1**, students' progress from basic understanding (*knows*) to autonomous action (*does*), fostering critical thinking and practical application.

Table 1. Levels of mastery of competences through the development of critical thinking skills for science education.

LEVELS OF SKILL DOMAINING (Adapted from Miller, 1990)	CRITICAL THINKING (Prado, Junyent and Oliveras, 2022)
Knows	Understanding, Analysis
Knows how	Valuation, Inference
Shows	Explanation, Approach to context
Does	Self-regulation, Intellectual autonomy

Prado, Junyent, and Oliveras (2022) emphasize critical thinking as central to achieving these competencies. Structured around the 5Rs, activities guide students from recognizing waste issues (*knows*), to proposing solutions (*shows*), and implementing actions (*does*). This iterative learning

aligns with Bruner's spiral curriculum (1960), which revisits concepts with increasing complexity.

By mastering the 5Rs, students connect personal actions to societal impacts, gaining scientific literacy, autonomy, and responsibility essential for sustainability and active citizenship.

Developing A Spiral To Learn The 5Rs

The spiral curriculum, proposed by Bruner (1960), introduces concepts at basic levels and revisits them with increasing complexity. This approach is particularly effective for teaching the 5Rs, as illustrated in Figure 1, were iterative learning fosters progressive understanding and application of waste management. Each R addresses a key aspect of waste management:

- Reduce: Avoid unnecessary consumption and minimize waste at the source.
- Redistribute: Sort waste to enable reuse, recycling, or recovery.
- Reuse: Extend product life through repurposing.
- Recycle: Transform materials into resources, reducing raw material use.
- Recover: Extract value from waste, such as nutrients or energy.

As shown in Figure 1, students revisit these Rs at increasing levels of complexity. For example, reducing waste begins with identifying unnecessary items (knows), progresses to evaluating bulk purchasing alternatives (knows how), leads to strategy design (shows), and culminates in real-world implementation (does). This progression mirrors Miller's levels of mastery (Table 1) and integrates critical thinking skills.

This iterative framework evolves with students, embedding critical thinking into activities, as highlighted by Prado, Junyent, and Oliveras (2022). It empowers learners to connect personal actions to societal and environmental impacts, fostering scientific literacy, autonomy, and responsibility.

Figure 1. Adapting Bruner's spiral for learning the 5Rs



Methodology

This study adopts a qualitative methodology to develop a Manual for solid waste management based on the 5Rs. The Manual combines playful and educational activities for each R, fostering engagement and learning. Its primary goal is to support teachers in promoting citizen science through a structured framework for environmental education.

Designed for both classroom and informal use, the Manual enables parents or guardians to participate alongside children, creating opportunities for collaboration and shared learning. This dual approach reinforces community involvement and encourages both children and adults to reflect on their waste management practices, fostering a collective commitment to sustainability.

Development Of A 5R Learning Manual

The 5R Learning Manual provides a structured yet flexible framework for teaching solid waste management to primary school students. It emphasizes practical, hands-on activities aligned with children's cognitive and developmental needs. The Manual includes clear objectives, detailed instructions, expected outcomes, and necessary materials to support effective learning.

Activities follow Miller's levels of mastery (Table 1), progressing from foundational knowledge (knows) to intellectual autonomy (does), fostering critical thinking and practical skills.

For instance, in the Reduce category (Table 2), activities like "Buy fresh and local products to reduce more" help students identify packaging types, consider bulk purchasing, and reflect on zero-waste principles through puzzles and reflections. These activities connect individual health with environmental sustainability.

The Manual supports both autonomous and guided learning, offering contextualized introductions, step-by-step methodologies, and reusable materials to reinforce resource efficiency. Its design ensures practicality for classroom and informal use, enabling parents or guardians to actively participate, fostering collaboration and shared responsibility.

By integrating critical thinking and sustainability principles, as proposed by Prado, Junyent, and Oliveras (2022), the Manual empowers students to connect personal actions to societal and environmental impacts. Following the spiral approach, activities build progressively, cultivating autonomy, reflection, and lifelong responsibility.

Table 2. Excerpt from the general structure of the 5R Manual.

5R	ACTIVITIES	OBJECTIVES AND METHODOLOGY
Reduce	Buy fresh and local products to reduce more	Through the cards and dates provided in the Manual, students learn to recognize different types of food packaging and reflect on how to reduce its use and volume. They are also encouraged to consider bulk purchasing to align with the zero-waste philosophy and complete a food pyramid puzzle to emphasize how individual health connects with sustainability and environmental health.
	Food Pyramid	
	Without packaging, like our grandparents did!	
	Reduce your waste to zero!	

5R Manual Validation Process

The validation of the 5R Learning Manual is a multi-stage process designed to ensure its effectiveness and relevance in fostering environmental education and critical thinking among primary school students. This paper focuses on the first two stages: the development of the Manual and its evaluation by expert educators. Subsequent stages, including practical classroom implementation and focus group analysis, will be addressed in future work.

The initial evaluation involved eight science teachers with extensive professional experience (a minimum of six years) and advanced academic qualifications (two Bachelor's, two Master's, and four Doctorate degrees). The teachers reviewed the Manual and completed a detailed

questionnaire designed to assess its quality and applicability. The questionnaire consisted of 20 items across six key dimensions:

1. Writing: Clarity, readability, and coherence of the Manual's content.
2. Relevance: Alignment of activities with the needs and developmental levels of primary school students.
3. Use of materials: Feasibility and accessibility of the resources required for the activities.
4. Objectives: Coherence between the stated objectives and the proposed activities.
5. Autonomy: Ability of the activities to promote independent learning among students.
6. Critical and creative thinking: Effectiveness in fostering higher-order thinking skills.

Responses were measured using a 5-level Likert scale, ranging from “strongly disagree” to “strongly agree.” Teachers who rated any item a 3 or below were asked to provide detailed feedback for improvement. This additional input ensured a robust and iterative refinement process for the Manual.

Preliminary results from this evaluation indicate that the Manual is well-structured and effective in achieving its intended objectives. Teachers highlighted the clarity of the writing, the relevance of the activities, and the appropriateness of the materials. They also suggested integrating a unifying narrative or theme to further enhance student engagement and motivation, such as a story with challenges that link the activities cohesively. These insights will guide future iterations of the Manual to ensure its continued effectiveness and adaptability in various educational contexts.

Results And Discussion

The validation process of the 5R Manual involved an in-depth evaluation by eight expert teachers, who provided feedback on six critical dimensions of its design and applicability. Key findings are summarized below:

1. Writing: The Manual’s content was praised for its clarity, conciseness, and accessibility for teachers, parents, and guardians. Respondents noted its balance between scientific rigor and accessibility, ensuring relevance across diverse contexts.
2. Relevance: Activities were deemed appropriate for primary students and aligned with their developmental needs. Teachers valued the real-world connections and suggested additional complementary exercises to enhance the Manual’s scope.
3. Use of materials: The resources required for the activities were practical, easily obtainable, and simple to handle. This accessibility was noted as a strength, reducing barriers to implementation.
4. Objectives: The stated objectives were coherent with the activities and effectively guided intended learning outcomes, fostering critical and creative thinking.
5. Autonomy: Activities were effective in promoting independent learning while maintaining a balance between guided and autonomous tasks, allowing students to develop self-regulation and decision-making skills.
6. Critical and creative thinking: The Manual was recognized as a valuable tool for fostering higher-order thinking skills. Teachers suggested adding a unifying narrative or theme to further motivate students and contextualize the activities.

Overall, feedback reinforced the Manual's effectiveness as an educational tool, highlighting its potential to meaningfully engage students in sustainability education. These insights will inform iterative improvements to ensure the Manual continues to meet the needs of educators and students.

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"The Living Things In Our Schoolyard": Design Of A Teaching-Learning Sequence For Primary Education

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The study of living beings and their classification is part of the curriculum in Primary Education. However, its study is often disconnected from the study of the relationships of interdependence between living beings and their habitats or problems associated with the loss of biodiversity. Therefore, in accordance with most Primary Education curricula, it is important that students acquire a general understanding of the organization of living things and their interaction with its environment, along with knowledge about local ecosystems and the services they provide. In that sense, many proposals and teaching materials to learn about biodiversity in primary education are available, but there is a pressing need to evaluate the potential of the naturalized school grounds to promote a deep understanding of this concept. We present a proposal for the design of a teaching-learning sequence (TLS) about biodiversity using the school's green space and its habitats. This proposal follows a Design-Based Research (DBR) methodology, because it offers an iterative process of design, implementation, evaluation and refinement, in an attempt to get a specific product - in our case a TLS - explicitly based on research results. We present results derived from the design phase using the DBR methodology, which involved the analysis of the school context through qualitative observational data from a pilot implementation in a 4th year primary classroom, definition of learning objectives and learning demands, to sketch a TLS about biodiversity in Primary Education.

Keywords: Teaching Learning Sequences, Biodiversity, Habitat, Primary Education, Ecodependence

Introduction

Biodiversity loss, one of today's most urgent socio-environmental crises, is closely linked to the growing disconnection between people—particularly children—and the natural world, which hinders the development of ecological understanding and the acquisition of knowledge about biodiversity and ecosystems that underpins sustainable lifestyles (Lindemann-Matthies, 2005; Lindemann-Matthies & Hyseni, 2009; Barrutia et al., 2022). Within Primary Education, the scientific model of living beings is a core curricular concept whose effective teaching benefits from the study of familiar animal and plant species in students' everyday environments and from direct, place-based experiences that enhance interest, connection with nature and understanding of environmental complexity (Willard, 2014; Gómez-Galindo et al., 2007). In this context, school green spaces—vegetated areas within school grounds, including school gardens and other outdoor learning environments—constitute authentic educational settings, comparable to classrooms or laboratories, with demonstrated potential to foster meaningful learning, well-being and community health and to contribute to competence-based learning and ecosocial resilience (Williams & Dixon, 2013; Chiumento et al., 2018; Eugenio-Gozalbo et al., 2019; Rammou et al., 2024; Aragón & Erdozain, 2025). There is thus a need for teachers to become familiar with these environments and with pedagogical approaches that leverage their potential, such as guided inquiry, which structures oriented research activities that reproduce essential aspects of scientific practice and position the instructor as mediator of learning rather than transmitter of knowledge (Rivero et al., 2011; Grossman, 2018). The integration of guided inquiry within school gardens enables learners to encounter biodiversity as a living, evolving reality, linking abstract ecological concepts to direct empirical experience and supporting conceptual change and the development

of ecological literacy in real contexts (Eugenio-Gozalbo & Ortega-Cubero, 2024; Ayotte-Beaudet et al., 2025; Doychinova, 2023).

With this in mind, we propose a Teaching-Learning Sequence (TLS) for Primary Education contextualized in the habitats of a school green space, developed within a Design-Based Research (DBR) framework in which TLSs function both as research interventions and curriculum products, refined through iterative cycles of design, implementation, evaluation and redesign to address students' learning difficulties and local contextual characteristics (Méheut & Psillos, 2004; Juuti & Lavonen, 2006; Guisasola et al., 2023). The contribution reported in this paper focuses on the Design phase, in which we analyse the school context, conduct an epistemological analysis of biodiversity and habitats, and define learning goals and associated learning demands—understood as the gap between intended objectives and students' prior ideas—while adding a distinctive element: the contextual analysis is complemented by qualitative evaluation of a draft TLS, including pilot implementation of selected activities in the school green space, to inform the refinement of design tools, teaching strategies and learning trajectories before full implementation (Barab & Squire, 2004; Leach & Scott, 2002).

Method

The Design-Based Research (DBR) methodology for Teaching-Learning Sequences (TLSs) comprises three general phases: i) Design, ii) Teaching experiments, and iii) Retrospective analysis (evaluation and refinement of the TLS) (Guisasola et al., 2023). In this paper, we focus exclusively on the Design phase.

Contextual Analysis Through A Pilot Implementation

The research team designed and organised the TLS around an initial scenario that asks whether students can mention at least five organisms living in the school green space. From this scenario, a set of driving questions was developed to address three key ideas: 1) diversity of living things, 2) living things and their habitats, and 3) eco-dependent humans. A preliminary version of the TLS, adapted from a sequence originally designed in the context of pre-service primary teacher education (Rico et al., 2026), was piloted with a 4th-year primary class, focusing on key ideas 1 and 2, to gather contextual implementation data. This contextual analysis was conducted through external observation by the third author and focused on (a) implementation constraints (clarity of activities, time allocation, pedagogical feasibility) and (b) learning constraints (students' difficulties) (Coronel-Gastiain et al., 2025). Data sources included the observer's notes from each session and notes from post-implementation meetings with the primary school teachers, where practical challenges were discussed. These implementation and learning constraints (educational, material or scientific), which may limit students' learning (Kariotoglou, 2003), were used, together with other DBR tools, to design and tailor the TLS to 4th-year primary students.

Definition of Learning Objectives and identification of Learning Demands

The definition of learning objectives is a central step in TLS design. In our case, three elements were considered: i) analysis of the Primary Education curriculum, ii) a literature review focused on learning difficulties related to biodiversity and ecosystems at this level, and iii) an epistemological analysis of the concept of biodiversity and its relevance. The analysis of the school context determines the conditions under which the TLS will be implemented; beyond curriculum standards, it includes students' feedback and socio-cultural characteristics of the setting, which is essential when comparing results across schools or countries and responds to calls to better specify contextual factors in TLS design and evaluation (Cobb et al., 2003). The TLS is intended for implementation from the 4th year of Primary Education onwards, whenever biodiversity and ecosystems are addressed in the curriculum.

An epistemological analysis of biodiversity—which examines both its historical development and current scientific models and theories (Chu et al., 2021)—allows us to define learning goals (LG) grounded in disciplinary epistemology rather than school tradition. This is crucial both for evaluating students' achievement and for obtaining valid evidence on TLS effectiveness. The second key element is the analysis of the gap between these LG and students' typical learning difficulties, as identified in the literature. These learning demands are understood as the ontological and epistemic distance between students' ideas and the scientific concepts, and they guide the organisation of the TLS by indicating the type and degree of difficulty that students are expected to encounter. Larger learning demands require more specific and sustained instructional support (e.g., more activities, scaffolding), whereas smaller demands can be addressed with fewer or less intensive interventions (Guisasola et al., 2023; Ruiz-González et al, 2025).

The designed TLS, "Our school's biodiversity", proposes an experiential approach to biodiversity through guided inquiry in the school green space. Starting from students' initial models of living beings, students sample the different habitats in a naturalised area of the school to investigate its biodiversity. The design is structured around: i) Driving Questions (DQ) linked to the key ideas about biodiversity, ii) LG associated with each DQ and set of activities, which guide students towards constructing explanations for each key idea (Guisasola et al., 2023), and iii) the scientific procedures to be carried out by students. Learners work in collaborative groups and record their observations and reasoning in a student workbook, which also serves as a data source for subsequent phases of the DBR cycle.

Results And Discussion

Observed Constraints In The Pilot Implementation

A series of selected activities was piloted in a 4th year PE classroom in 2024, where the topic of living things and ecosystems was being taught. These practical activities were directed towards the examination and sampling of different habitats in a park near the school and a visit to the university organic garden at the end of the sequence (Figure 1). The implementation was carried out during the third term, between April and June in parallel with the classroom instruction on ecosystems conducted by the Primary Education teachers. This pilot version comprised a total of seven activities. Figure 1 (next page) presents the overall structure of the proposed sequence.

Based on the data obtained from the qualitative tools, such as the external observer's report and post-implementation meeting notes, we identified several constraints in the pilot, mostly in the material and the scientific domain (Kariotoglou et al., 2003). For example, students could predict some of the living things that could be found in their schoolyard or nearby park, but they could not depict their particular habitat, and this hindered the subsequent sampling activity. These scientific constraints also informed the definition of some learning demands, as we will show in the following section. A clear material constraint was the consideration that going outside was not a cooperative academic task, and 4th year students struggled to understand that field sampling involves a set of particular rules and procedures. A summary of constraints identified in the implementation for two activities and design decisions are shown in Table 1.

Epistemological Analysis And Definition Of Learning Goals

This pilot implementation informed the sketch and design of a TLS specifically targeted to Primary Education children. As stated in methodology, the proposed TLS was designed based on the epistemological analysis of the concept of biodiversity by looking at both its historical development, and current models and theories that allow scientific explanations about biodiversity (Chu et al., 2021).

Figure 1. Sequence of the activities

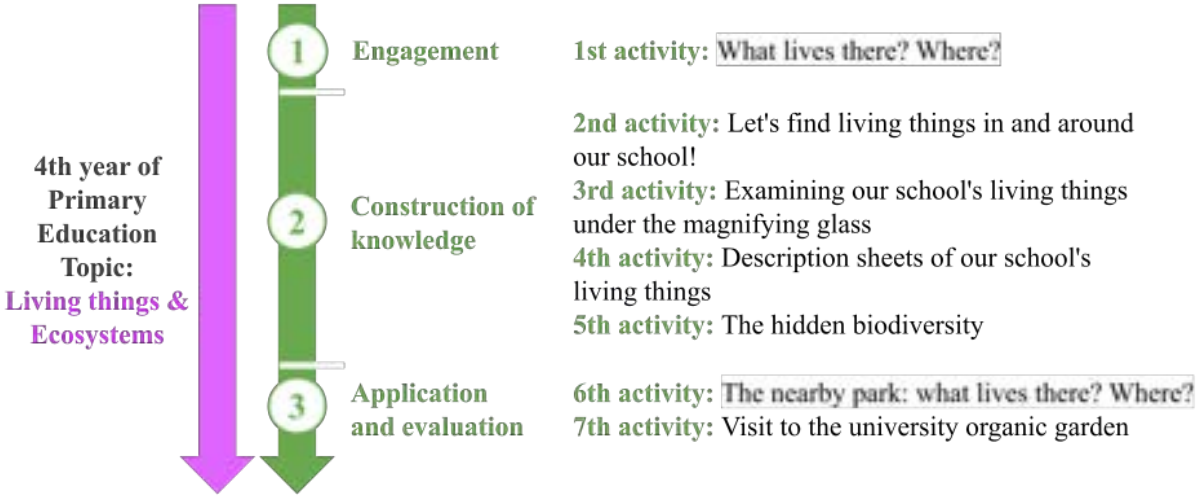


Table 1. Designed decisions based on observed constraints found in two activities of the pilot implementation.

Example of activities	Observed constraints	Design decision
Detecting student's initial ideas What lives there? Where?	Students can enumerate living things, but they have difficulties predicting where each one can be found. Although some examples were given, students were not able to represent the "habitat".	When covering the topic of living things and its classification, the concept of habitat must be explicitly taught.
Guided inquiry activity Let's find living things in and around our school!	Students show plant awareness disparity and do not consider them worth collecting or registering. Rule abiding and collaborative work while collecting data proved to be difficult.	Include a dedicated session to plant identification. Introduce students to the methods of sampling and data collection in a controlled space before exploring wider areas such as parks.

Biodiversity encompasses the variety of living organisms at genetic, species, and ecosystem levels, as defined by the Convention on Biological Diversity (United Nations, 1992), and includes not only species richness but also their relative abundance and functional roles within ecosystems (e.g., producers, consumers, decomposers) that enhance ecosystem resilience (Campbell et al., 2020). For 9-10-year-old children, this epistemology translates into five key learning goals aligned with primary curriculum standards: E1) recognizing millions of different living things with varying similarities; E2) grouping them by shared characteristics; E3) understanding species populations in specific habitats with suitable conditions for survival; E4) appreciating human well-being's dependence on other living beings and environments; and E5) identifying human impacts like habitat destruction, pollution, overexploitation, invasive species, population pressure, and climate change that threaten biodiversity (Campbell et al., 2020; Millennium Ecosystem Assessment, 2005; Willard, 2014). This focused framing grounds TLS design in disciplinary knowledge while addressing children's learning demands, such as scaling from observable school habitats to global concepts and normative conservation values (Navarro-Perez & Tidball, 2012).

The definition of our learning goals (see Table 2) is anchored in this epistemological analysis, instead of relying on textbooks or particular teaching styles (Guisasola et al., 2023). These indicators are measurable and will form the basis of specific open-ended questionnaires and teaching strategies to evaluate students' learning.

Table 2. Learning goals that define the concept of biodiversity and habitats in a TLS for Primary Education.

Elements from the epistemology of biology	Learning goals
E1. There are millions of different living things on Earth, some are very similar to each other, while others are very different.	**LG1.** To understand that there are many kinds of living things
E2. Living things can be classified into different groups based on their shared characteristics and features.	**LG2.** To learn to classify living beings into different groups according to their characteristics. **LG2.1.** To learn to distinguish and classify different types of animals. **LG2.2.** To learn to distinguish and classify different types of plants.
E3. Populations of particular species live in a specific place, which is called a habitat. The physical conditions and resources of the habitat must ensure the survival and reproduction of such a population.	**LG3.** To understand that there are different habitats at different scales according to physical conditions. **LG4.** To understand the connection between living beings and specific habitats and that changes in those habitats affect the organisms living there. **LG4.1.** To know which living things live in the immediate environment.
E4. Our well-being depends on the well-being of other living beings and the environment.	**LG5.** To understand the benefits or contributions that biodiversity (nature) offers to people. **LG6.** To understand that humans depend on nature (eco-dependency)
E5. Human activities have negative consequences on biodiversity due to: i) excessive human population; ii) overexploitation of natural resources; iii) habitat destruction, iv) pollution; v) introduction of invasive species and vi) climate change.	**LG7.** To know the impacts that humans have on nature and understand that we have the ability to influence it both positively and negatively.

Table 3. Alignment of Learning Difficulties with Learning Goals and identification of Learning Demands for a TLS about biodiversity in Primary Education

Learning difficulties	Learning demands	Learning Goal

• Difficulties in distinguishing between living and non-living beings (Driver et al., 1994). • Difficulty of naming taxons, other than mammals (Lindemann-Matthies, 2005). • Plant and native species awareness disparity (Barrutia et al., 2022). • Anthropocentric thinking (domestic, farming, cultivated,..) (Coronel-Gastiain et al., 2025)	Low Medium High Low	LG1
• Difficulties in biological classification skills and use of keys (Lindemann-Matthies, 2005).	High	LG2
• Limited knowledge about habitats makes it difficult to relate a specific living being to a habitat (Marulcu, 2014; Savvaidou-Kambouropoulou & Skoumios, 2012)	Medium	LG3 LG4
• Ignoring that biodiversity provides us with benefits other than material ones (e.g. regulatory services) (Rodriguez-Loinaz et al., 2022). • Lack of understanding of the normative dimension of biodiversity for conservation measures (Lindemann-Matthies et al., 2009).	Medium High	LG5
• Lack of awareness of the importance of biodiversity in the health of the planet and people (Menzel & Bögeholz, 2009).	Medium	LG6
• Lack of criteria to decide on effective measures for improving biodiversity (Rammou et al., 2024). • Lack of perception of the consequences of daily decisions (good or bad) on local biodiversity (Rammou et al., 2024).	High High	O7

Table 3 shows an example on how the definition of learning goals and the identification of learning difficulties allows for the identification of our student's expected learning demands. This is a pre-requisite to design appropriate teaching strategies, activities and evaluation tools. Primary students commonly struggle to distinguish living from non-living beings at an early age (Driver et al., 1994) and show limited recognition of plant and native species beyond familiar mammals, reflecting persistent biodiversity awareness disparities (Lindemann-Matthies, 2005; Barrutia et al., 2022). They often exhibit anthropocentric biases favoring domesticated species, face challenges in biological classification and using identification keys (Lindemann-Matthies, 2005), and struggle to link organisms to specific habitats due to limited ecological knowledge (Marulcu, 2014). Additionally, they overlook non-material ecosystem services, fail to grasp biodiversity's normative conservation dimension (Lindemann-Matthies et al., 2009; Torkar & Krašovec, 2019), and lack awareness of how daily decisions impact local biodiversity or criteria for effective conservation measures (Rammou et al., 2024). Despite these challenges, Primary Education students show high engagement and rapid learning when studying living things and nature through hands-on, inquiry-based activities in familiar contexts like school gardens, where they exhibit greater motivation, curiosity, and science achievement compared to traditional classroom

settings (Dillon et al., 2006; Randler, 2008). Table 3 illustrates how these documented learning difficulties align with our learning goals to determine the corresponding level of learning demands (Leach & Scott, 2002).

Conclusion

We have presented an application of the DBR methodology for designing a TLS about biodiversity contextualized in the school green space for Primary Education, which will form the basis of a broader research program validating evidence-based TLSs in primary science education. A key novelty of this work lies in the contextual analysis conducted through pilot implementation of selected activities transposed and adapted from a TLS originally designed for pre-service primary teachers (Rico et al., 2026). This preliminary testing with 4th-year students provided critical data on implementation constraints (activity clarity, timing, feasibility) and learning obstacles, enabling us to tailor the TLS more precisely to primary learners' needs and school realities before full-scale development. As stated previously, the early DBR phases anchor the TLS robustly by integrating epistemological analysis of biodiversity, curriculum requirements, and documented learning difficulties from the literature. Further work involves defining instructional strategies to foster biodiversity understanding, while subsequent phases will evaluate the sequence's quality and learning outcomes to refine the TLS and generate empirical evidence on primary students' conceptual grasp of biodiversity, its ecological significance, and the impact of school green space interventions.

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Bridging Classical And Modern Physics: An Integrated Astronomy Curriculum For Primary Schools

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General Relativity, despite its central role in contemporary science, remains largely absent from school education. At the same time, research in science education shows that traditional instruction often fails to promote deep conceptual restructuring, leading to the persistence of misconceptions, particularly in astronomy. This paper presents an experimental study in physics and astronomy education that investigates whether integrating core principles of General Relativity into an astronomy curriculum can support the development of scientific competences. The intervention, conducted in Italian primary school, included activities focused on spatial reasoning and the use of reference frames, followed by the introduction of the basic ideas of light and gravity from a relativistic perspective. Data analysis is currently ongoing. The study discusses the potential of this approach to contribute to the renewal of science curricula.

Keywords: astronomy education, primary school, Einsteinian physics.

Introduction

In science, models play a central role in shaping how phenomena are interpreted and explained. Since the epistemological transformations of the early twentieth century, science has increasingly been understood not as a linear accumulation of empirical data, but as a coherent theoretical system grounded in conceptual models that guide observation, experimentation, and meaning making (Kuhn, 1962; Geymonat, 1972). From this perspective, empirical evidence cannot be separated from the theoretical framework in which it is embedded, as all observation is inherently theory-laden (Hanson, 1958). The formulation of General Relativity in 1915 represented a major paradigm shift in the understanding of space, time, and gravity, profoundly reshaping the scientific image of the world (Cassirer, 2015). Despite its foundational role in modern physics and cosmology, this theory remains marginal in compulsory schooling. In particular, astronomy education continues to rely mainly on classical models, with limited attention to the epistemological implications of modern physics.

At the same time, research on science learning has long documented the persistence of intuitive conceptions that are resistant to formal instruction, highlighting the limitations of traditional teaching practices in fostering deep conceptual change (Ausubel, 1968; Driver & Easley, 1978; Novak, 1987; Trumper, 2000). In astronomy education, these difficulties are especially pronounced and affect both students and teachers, contributing to low levels of conceptual understanding and to disengagement from the discipline (Atwood & Atwood, 1996). Current theoretical interpretations of these learning challenges are mainly framed within the Knowledge in Pieces Theory (diSessa, 2018) and the Framework Theory (Vosniadou, 2019). However, empirical studies explicitly examining how the adoption of different scientific models influences learning processes and the construction of a view of the universe remain scarce (Plummer et al., 2015).

Considering this context, physics education requires a non-hierarchical integration of epistemological, cognitive, and instructional dimensions (Gagliardi & Giordano, 2018). From this perspective, the present study investigates whether and to what extent the introduction of selected core concepts of General Relativity can support learning and motivation in primary school. Situated at the intersection of physics education research and educational science, the

study designs and implements instructional sequences in fifth-grade classrooms, embedded within a broader astronomy curriculum conceived as an epistemic context for constructing meanings consistent with a modern physical–cosmological perspective. The study is currently ongoing, and data analysis has not yet been completed; therefore, this paper focuses on presenting the research design and the structure of the experimental intervention, which is part of a broader ongoing study.

Research In Astronomy And Physics Education

Research in the field of science education has long demonstrated that the practice of science teaching is frequently characterised by fragmentation and a lack of coherence. The pedagogical approach is typically predicated on linear and cumulative models, which are observed to have difficulty in reflecting the intricacies inherent in the learning process (Adams & Slater, 2000). In response to these limitations, numerous studies have emphasised the necessity to reconsider instructional design, commencing from Big Ideas, which are defined as conceptual macro-structures with the capacity to integrate and interpret a broad array of phenomena, situations and problems, thereby furnishing a unifying explanatory framework for comprehending the natural world (Plummer, 2012). Despite the absence of a unifying definition of a Big Idea in the extant literature, the various classifications proposed do align in acknowledging their role in the organisation of science instruction (Slater & Slater, 2009; Lelliott & Rollnick, 2010).

Big Ideas are closely connected to Learning Progressions, which are theoretical models that describe learning trajectories characterised by increasingly sophisticated levels of understanding. These models are grounded in empirical evidence on students' conceptual development (Rogat et al., 2011). Rather than representing a simple incremental accumulation of knowledge, these models aim to depict qualitative transformations in understanding, accompanied by increasing cognitive and epistemological complexity (ibid.). From this perspective, big ideas and learning progressions can be interpreted as complementary components of the same curricular structure: the former function as core conceptual nodes, while the latter outline the trajectories through which these nodes are progressively reorganised and deepened over time.

Despite the theoretical relevance of this framework, the literature highlights persistent difficulties in translating such models into coherent curricular designs, particularly with regard to the teaching of modern physics and astronomy concepts. In addition to theoretical contributions, a considerable number of instructional interventions focusing on specific physical and astronomical subjects have been developed. However, as Plummer et al. (2015) have noted, a perspective that systematically investigates the connections among these aspects within a coherent, progressive and long-term view of astronomy learning is still lacking. This limitation renders it challenging to ascertain the extent to which the adopted theoretical models influence learning processes and the construction of a coherent scientific view of the universe.

Within this context, the present study builds on two main strands of research. The first concerns the study of the apparent motions of celestial bodies, with particular reference to the experimental work of J. Plummer, who proposed a Learning Progression model in this domain. The secondary strand encompasses studies that are oriented towards the integration of contemporary physics and non-Euclidian geometry within educational settings. Among the most relevant initiatives is the Einstein First project, developed at the University of Western Australia, which has led to a vertical curriculum implemented in approximately sixty schools, from early childhood education to upper secondary school, integrating selected concepts of modern physics (Blair & Kersting, 2021; Popkova et al., 2021; Foppoli et al., 2018; Kaur et al., 2017, 2023; Choudhary et al. 2022). Complementary contributions are provided by the research of Kersting (2019; 2021) in secondary education and by the instructional experiments conducted by Gambini (2021) in primary school,

aimed at introducing Euclidean and non-Euclidean geometry in an integrated and parallel manner from the early years of schooling.

While the extant studies reviewed here provide relevant contributions to the field, there is a need for further methodological refinement and greater attention to the transferability of results across different contexts.

Research Questions

In this framework, there is a necessity to develop studies that combine greater methodological robustness with a more systemic approach to disciplinary content. This would be capable of enhancing the conceptual and curricular integration of the different dimensions of astronomical and physical knowledge. In this study, the objective is to examine the hypothesis that integrating classical and modern paradigms in teaching can facilitate the development of scientific skills. This aspect represents one of the dimensions explored within a broader research project. Specifically, the hypothesis is that the systematic introduction of Einsteinian physics principles within an astronomy curriculum from primary school onwards has the potential to enhance students' scientific competence.

The research therefore aims to answer the following questions: i) In what ways does the learning of astronomy vary in relation to a curriculum that is more or less structured and integrated with Einsteinian physics principles? ii) What are the effects in terms of learning in socio-economically disadvantaged student groups? iii) What exogenous factors influence the achievement of these objectives?

The objectives of the research can thus be stated as follows: i)Analyse the impact of integrating Einsteinian physics into the teaching of astronomy on improving science skills; ii) Investigate the relationship between learning and the ESCS (*Economic, Social and Cultural Status*) indicator; iii) Investigate the impact on teacher training; iv) Contribute to the delineation of Learning Progress in the field of General Relativity.

Method

In view of the theoretical framework that has been presented and the necessity for further in-depth research, it was decided to adopt a quasi-experimental design with quantitative and qualitative data collection. On the one hand, the quantitative approach engenders results that are statistically stable and extends the conclusions to a broader context. Conversely, the integration of qualitative data facilitates the capture of the intricacies, variability and distinctive characteristics of the individual experimental groups and students involved, thereby circumventing an excessive reduction in the richness of information that is characteristic of educational experiences. A qualitative analysis is also necessary given the exploratory nature of research in the field of modern physics teaching in primary schools.

Three public primary schools in the Turin urban area were selected with average, medium-low and low ESCS indicators, based on the reports of the individual schools for the last two school years. The sample was selected on the basis of the research objectives, namely to investigate the relationship between the development of scientific skills and the ESCS indicator; therefore, it is not a random sample, but a reasoned one. The project was presented to three different public schools and was aimed at 4th and 5th grade classes, specifying the number of experimental groups required for each school. Participation in the project was voluntary. Four classes were selected for each school, corresponding to four experimental groups, for a total of 12 experimental groups and N=255 students. In particular, the following groups were established:

• G1: group in which a complete intervention by the researcher was tested in the 5th year primary class during the first term (complete group 1);

• G2: group in which a complete intervention by the researcher was tested starting from the 4th year primary class (complete group 2);

• G3: group in which the 5th grade class followed the teacher's educational programme and the researcher carried out a series of sporadic interventions during the first term (*spot* group);

• G4: control group.

Four experimental groups were created to analyse changes in variables based on different teaching choices. Firstly, a time frame similar to that usually adopted in Italian schools was utilised, i.e. condensing the teaching of astronomy into approximately five months of Year 5 primary school. This choice was linked to the availability of the teachers themselves. Concurrently, it was necessary to understand how learning varies when the teaching intervention is presented before the fifth year of primary school. The findings of research in this area indicate that there is no age below which it is impossible to introduce scientific teaching, on condition that it is calibrated according to the level of complexity that the child can manage (Levrini & Fantini, 2013). Consequently, the G2 group was identified, and the intervention was initiated in Year 4. These activities focused on the development of the necessary prerequisites related to the apparent motions of celestial bodies, as a basis on which to build future learning starting in Year 5 of the following school year.

Lastly, the G3 group was introduced, named “spot” for being a group in which the researcher carried out sporadic interventions in the classroom, in order to compare how learning varied between a complete curriculum, in which elements of classical and modern physics were integrated within the course, and a traditional one, conducted entirely by the teacher, in which the external specialist inserted himself and superimposed some activities specifically related to General Relativity. The choice adopted responds to the need to assess the effectiveness and transferability of short-term teaching interventions carried out by non-school personnel, a typology that is now widespread in the contemporary Italian school context. The division into experimental groups allows a comparative analysis of the outcomes, taking into account the differences between the experimental interventions and the socio-economic (ESCS) and gender characteristics of the participants.

An in-depth study on teacher training was planned to analyse the perceptions of the teachers involved and understand how they attributed meaning to the teaching experience, exploring how the proposal was integrated into professional practice and its contribution to the development of shared skills in the school community.

Knowledge And Skills Involved In The Curriculum

Following the operationalisation of the construct of scientific competence on the basis of international literature, the fundamental conceptual nodes of the curriculum were identified and developed. The experiment employed the Pedagogical Content Knowledge (PCK) model in an attempt to integrate the following criteria: i) content knowledge; ii) curriculum knowledge; iii) knowledge of students' difficulties and misconceptions; iv) knowledge of learning assessment; v) knowledge of teaching strategies (Magnusson et al., 1999). The curriculum was then constructed on the basis of a selection of four Big Ideas from those proposed in the literature:

- *Apparent motions of the Sun, Moon and starry sky.* Based on Vosniadou's studies (Vosniadou, & Brewer, 1994) on the patterns of naïve knowledge possessed by children,

Plummer (2012) points out that apparent motions represent the crucial conceptual node and fundamental prerequisite for any future learning of astronomy.

- *Dimensions and distances*. It is widely acknowledged that the comprehension of cosmic dimensions and scales constitutes a fundamental intellectual concept that is notoriously challenging to master, particularly during primary school education (Lelliot & Rollnick, 2010). Despite its relevance, this aspect receives little attention in school curricula and textbooks, with frequently present distorted representations of the Solar System (Testa et al., 2014). This fosters the development of misconceptions that often persist well into adulthood (ibid.).
- *Dynamic properties of planets*, in which the concept of gravity is directly involved. Several studies have examined the misconceptions held by children and adolescents about this phenomenon (Bar & Zinn, 1998; Baldy, 2007; Bar et al., 2016), particularly emphasizing a geocentric view that frames gravity as a phenomenon limited to the Earth. However, despite these contributions, research on gravity within astronomy education remains scarce, and the topic is still marginal in school curricula, likely because of its abstract character and the challenges associated with making it accessible in educational settings. In addition, the majority of existing studies focus on instruction grounded in the Newtonian framework. From this perspective, General Relativity remains among the least investigated topics in educational research (Blair & Kersting, 2021). Within the Big Ideas approach, gravity can therefore be addressed in schools not only through the Newtonian paradigm, but also by introducing elements of General Relativity. Didactic tools such as the *elastic sheet* model (Kaur et al., 2017), while limited, are particularly useful in making changes in gravitational attraction visible as a function of mass, orbital speed around a central body, and that body's capacity to dominate the surrounding space gravitationally.
- *Stars*, with emphasis on the difference between stars and planets. In this regard, the primary distinguishing factor between stars and planets is light, rather than the nuclear reactions characteristic of stars. The concept of light and its properties is of significant importance and merits particular attention from the earliest stages of education, particularly pre-school (Leone, 2020).

After translating the Big Ideas into specific learning objectives, these were integrated with key conceptual elements of General Relativity, which were also defined in relation to the same objectives. The conceptual elements identified as relevant included: (i) gravity, (ii) reference frames, (iii) light, and (iv) geometry on curved surfaces. These elements were then incorporated within the corresponding Big Ideas.

Research Instruments

The literature proposes several standardised instruments for the detection of conceptual understanding in science, such as concept inventories (Lindell, 2001; Bardar et al., 2006; Sadler et al., 2009). However, such instruments are limited with respect to the assessment of scientific competences, particularly in astronomy, as they are designed for secondary school and are predominantly performance-oriented and do not allow for the systematic investigation of attitudes and processes underlying competence (Allal, 1999). Similarly, large-scale surveys such as PISA and TIMSS (OECD, 2019; Mullis & Martin, 2023) do not consider astronomy as a stand-alone area of assessment.

This framework highlights a structural problem in the detection of scientific competences, understood as the integration of knowledge, processes and attitudes, in line with a view of science as evidence-based model building (Gagliardi & Giordano, 2018). Consequently, it became necessary to design a purpose-built assessment tool. Starting from the conceptual cores and the

specific objectives identified, a semi-structured test was developed for the detection of knowledge and skills, integrated with Guilford's (1967) model of cognitive processes and flanked by qualitative instruments aimed at investigating attitudes, considered to be the foundations of competence in astronomy. Participant observation, the authentic task and an evaluation rubric inspired by Allal's (1999) criteria were used.

The analysis was further deepened through semi-structured interviews aimed at teachers, designed from the logbooks and conducted according to an inductive bottom-up approach (Birks & Mills, 2015), in order to integrate the data collected and bring out the meanings attributed to the teaching experience.

Limitations And Perspectives Of The Research

At present, no definitive conclusions can be drawn, as the study is still in the experimental phase and data collection is ongoing. Nevertheless, some preliminary considerations regarding the strengths and limitations of the research can be outlined. The intervention may represent a step toward an approach to astronomy education in Italian primary schools that is more consistent with the epistemology of science and with constructivist perspectives on learning. In contrast to current instructional practices, which in astronomy remain largely grounded in traditional models and often show limited effectiveness in supporting conceptual restructuring and the development of complex scientific competences, the present design explores alternative instructional pathways. At the same time, disciplinary didactics involves substantial methodological complexity, as it requires the integration of multiple dimensions, including epistemological aspects related to the structure of physical concepts, instructional and methodological choices concerning teaching strategies and activity sequences, and cognitive aspects related to students' intuitive conceptions and processes of conceptual change.

A relevant limitation concerns the assessment instruments adopted, which present constraints in terms of validity. The astronomy test was specifically developed for this study, and, due to limitations related to sample size and intervention duration, it was not possible to conduct a preliminary exploratory factor analysis to examine its latent structure. For this reason, quantitative analyses of test scores should be complemented by qualitative analyses of open-ended responses, allowing for comparisons between experimental groups in relation to the differentiated instructional conditions. From a data triangulation perspective, test results will need to be interpreted alongside qualitative evidence, such as systematic classroom observations, audio or video recordings, and students' written artefacts, in order to better capture the processual nature of learning and to situate students' responses within their instructional context.

An additional point of interest concerns the introduction of concepts, such as reference frames, that are not typically addressed systematically in primary school curricula. This offers an opportunity to explore how students engage with such concepts and how their initial intuitive conceptions may be reorganized through the proposed activities.

Finally, the scope and diversity of the collected data suggest the potential to inform future research on Learning Progressions related to apparent celestial motions and, more broadly, to support further investigations into concepts such as gravity, whose Learning Progressions have traditionally been framed within a Newtonian perspective. In this contribution, however, these issues are not examined analytically; rather, they are outlined as directions for subsequent work, particularly with respect to the integration of alternative theoretical models into instructional design and the investigation of students' cognitive processes through longitudinal and in-depth analyses.

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Part 18 / Strand 18

Teaching And Learning Science At Middle And Secondary School

Co-editors: *Ilídio André Costa & Dury Bayram*

Part 18 / Strand 18 Teaching And Learning Science At Middle And Secondary School

Teaching and learning theories and practices related to content knowledge, pedagogical knowledge, pedagogical content knowledge, and instructional material, strategies and practices at the middle and secondary school levels.

Sub-themes:

1) Middle School Teaching
2) Middle School Learning
3) Secondary School Teaching
4) Secondary School Learning

Contents

Strand 18: Teaching And Learning Science At Middle And Secondary School.....1680

Facilitating Knowledge Interconnection Through Instructional Prompts In Chemistry Classroom Discourse – An Explorative Qualitative Single-Case Study 1681

Inclusive Science Education: Interest In Experimenting And Perceived Self-Efficacy In An Interdisciplinary Teaching Concept.....1691

Making Room Or Falling Into A Trap – Biology Teachers' Conceptions Of Evolutionary Lesson Planning 1698

Visualizing Chemistry: Analyzing Graph Usage In Textbooks And Its Implications For Teaching 1705

What Comes To Mind When You Think Of Mechanical Engineering? 1715

Uses Of Fault And Fold Models In Geoscience Education: A Case Study In Upper Secondary Education 1721

Strand 18: Teaching And Learning Science At Middle And Secondary School

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Introduction

This chapter showcases the commitment and creativity of teachers and researchers who strive to improve the quality of science education at both middle and secondary school levels.

Strand 18 examines the two contexts in which science education occurs: middle and secondary school. The studies presented in this chapter provide important insights into the specific challenges and opportunities that arise at these stages of the educational process.

The combined insights presented in this chapter highlight the essential role of teacher education in influencing the global development of science education. By integrating the contributions of researchers, educators, and practitioners, this chapter functions as both a valuable reference and a source of motivation for those dedicated to promoting meaningful science learning experiences in middle and secondary school settings.

We would like to acknowledge the efforts of the authors and conference organizers whose contributions made this proceedings book possible. We trust that the research presented here will support and encourage further dialogue and initiatives in the field of science education.

We encourage readers to engage with the wide range of perspectives presented in this collection and believe that the research included will inspire new ideas and contribute to the advancement of science education.

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Facilitating Knowledge Interconnection Through Instructional Prompts In Chemistry Classroom Discourse – An Explorative Qualitative Single-Case Study

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Interconnected knowledge structures are widely regarded as a key prerequisite for meaningful learning and the flexible application of subject matter in science education. Although curricula consistently emphasise cumulative and interconnected learning, classroom instruction often remains oriented toward the reproduction of fragmented and isolated knowledge. Against this background, the present study examines how instructional prompts within classroom discourse are related to the levels of interconnection evident in students' responses during chemistry lessons.

The study is based on an exploratory qualitative single-case study conducted in a ninth-grade chemistry class in Germany. Classroom discourse from a teaching unit on redox reactions in the context of electrochemistry was video-recorded and subjected to systematic analysis. Instructional sequences were identified and examined using a combined analytical approach that integrates a categorisation of levels of interconnection with sequential interaction analysis. Initiation, evaluation, and feedback prompts were derived through a deductive-inductive procedure.

The findings indicate that initiation prompts such as "name" and "describe", which occur most frequently in classroom discourse, are predominantly associated with lower levels of interconnection. In contrast, less frequent prompts inviting "assumption" or "explanation" tend to elicit responses characterised by higher levels of interconnection. Moreover, evaluation prompts often function to conclude instructional sequences and may therefore constrain opportunities for sustain cognitive engagement. Feedback prompts, by contrast, frequently extend instructional sequences and serve both regulative and elaborative functions. While feedback often maintains a stable level of interconnection by re-establishing symmetry between initiation and response, it can also be associated with an increase in the level of interconnection. The results further suggest that instructional sequences characterised by stable levels of interconnection may nevertheless allow for substantial depth of content through elaboration within a given level. Overall, the study highlights the importance of the deliberate design of initiation and feedback prompts in classroom discourse and offers insights into how instructional interaction can support cognitive activation and the development of interconnected subject matter understanding.

Keywords: Knowledge Interconnection, Classroom Discourse, Instructional Prompts

Introduction

From a learning psychology perspective, interconnected knowledge structures are considered essential for effective information processing and the development of (personal) competencies (Neumann et al., 2008). Accordingly, the curriculum emphasises interconnected teaching and learning by encouraging students to relate newly acquired knowledge to their prior knowledge through repeated revisiting of subject matter at a progressively higher levels of abstraction across the school years. The long-term objective is to develop chemistry subject matter not merely in an additive manner, but also cumulatively, enabling students to apply their knowledge flexibly across diverse situational contexts (Conference of the Ministers of Education Germany (KMK), 2024).

Despite curricular guidelines in Germany that explicitly promote repetition and increasing abstraction of subject matter (Bruner, 1960; Ministry of School and Education (MSB NRW),

2019), empirical studies report a decline in science performance among German students (cf. Holtmann et al., 2019; Köller, 2024). This discrepancy between curriculum frameworks that account for cumulative learning processes and declining student achievement, which constrains students' ability to meaningfully interconnect subject matter concepts, can be attributed to several factors. First, the hierarchical organisation of subject matter poses particular challenges for students with pre-existing knowledge gaps, making the integration of new knowledge more difficult (cf. Rother & Walpuski, 2020). Second, students often perceive the content taught as a collection of isolated facts, leading to the impression that chemistry instruction lacks coherence (cf. Bernholt et al., 2020; Rother & Walpuski, 2020). Third, students frequently struggle to engage deeply with learning objects due to insufficient cognitive activation in science classrooms (cf. Köller, 2024). Consistent with this, previous studies indicate that science instruction often prioritises reproduction of knowledge, resulting in comparatively low levels of knowledge interconnection (cf. Dietz & Bolte, 2022; Neumann et al., 2008; Podschuweit et al., 2016; Smart & Marshall, 2013; Xu et al., 2024).

Irrespective of country-specific curricular frameworks, cognitively activating and interconnected instruction – characterised by challenging learning tasks and structured teacher-student interactions within classroom discourse – is widely regarded as a key determinant of improved learning outcomes (Neumann et al., 2008; Schreyer & Charalambous, 2024). Against this background, the present study investigates cognitively activating interactions initiated by instructional prompts in classroom discourse as a potential factor influencing the interconnection of school-based chemistry subject matter.

Theoretical Background

Interconnected Learning

Interconnected learning refers to the integration of individual knowledge elements into higher-order cognitive structures through cumulative learning processes (Bernholt et al., 2020). It involves linking newly acquired knowledge to existing prior knowledge, thereby progressively increasing the complexity of learners' knowledge structures through processes of expansion and hierarchisation (Ausubel, 1960; Gagné, 1968; Harms & Bünder, 1999). Such increasingly complex knowledge structure offers several advantages. These include improved retention of interconnected knowledge compared to isolated factual knowledge, more efficient transfer and application of knowledge across different contexts and reduced cognitive effort during knowledge retrieval (Fischer et al., 2007; Mietzel, 2017; Kunter & Trautwein, 2018). Interconnected learning can be differentiated into two forms. Horizontal interconnection refers to interdisciplinary linkages between subject areas, whereas vertical interconnection describes intra-disciplinary connections that build upon one another over time (cf. Fischer et al., 2007). The present research project focuses on vertical interconnection within chemistry education, examining how chemistry subject matter is interconnected through verbal teacher-student interactions in classroom discourse.

Instructional Prompts In Classroom Discourse

Classroom discourse represents one of the most prevalent forms of instructional practices and it "is not merely a conduit for sharing of information […]; it is the most important educational tool for guiding the development of understanding and for jointly constructing knowledge." (Mercer & Hodgkinson, 2008). Within classroom discourse, students are encouraged to articulate their thinking verbally, thereby providing teachers with opportunities to respond through targeted instructional prompts that support learning processes (Kim & Lim, 2025; Lipowsky et al., 2021). Instructional prompts are brief, content-oriented hints, questions, or requests posed by teachers

to stimulate students' cognitive or metacognitive processes during classroom discourse without introducing new subject matter. This instructional approach is based on the assumption that students generally possess the relevant conceptual knowledge or procedural skills but may struggle to activate them spontaneously. Instructional prompts thus serve to direct students' attention to subject-relevant aspects and support activation and organisation of existing knowledge (Bannert, 2009; Current & Kowalske, 2016; Wirth, 2009). Despite consistent evidence of low levels of knowledge interconnection in science instructions (cf. Dietz & Bolte, 2022; Neumann et al., 2008; Podschuweit et al., 2016; Smart & Marshall, 2013; Xu et al., 2024), the role of instructional prompts in fostering interconnected knowledge structures, particularly across extended instructional sequences in classroom discourse, remains largely underexplored.

Research Project

Aim, Research Question And Study Design

The overarching aim of this study is to examine cognitively activating interactions in classroom discourse and their relationship to subject-related interconnection in chemistry lessons. To gain insights into authentic teaching practice, the study was designed as an exploratory qualitative single-case study and conducted in a ninth-grade chemistry class at a German Gymnasium over the course of an entire school year (cf. Yin, 2018). Ninth-grade students were selected due to their comparatively advanced prior knowledge, which provides increased potential for the interconnection of subject matter concepts (cf. Bernholt et al., 2020).

The empirical analysis focuses on a teaching unit on redox reactions in the context of electrochemistry (cf. MSB NRW, 2019), which was fully video-recorded. Within this instructional context, the study investigates strategies employed in classroom discourse to foster subject matter interconnection. The analysis is guided by the following research question: Which instructional prompts are used in classroom discourse, and to which levels of interconnection do students' responses lead?

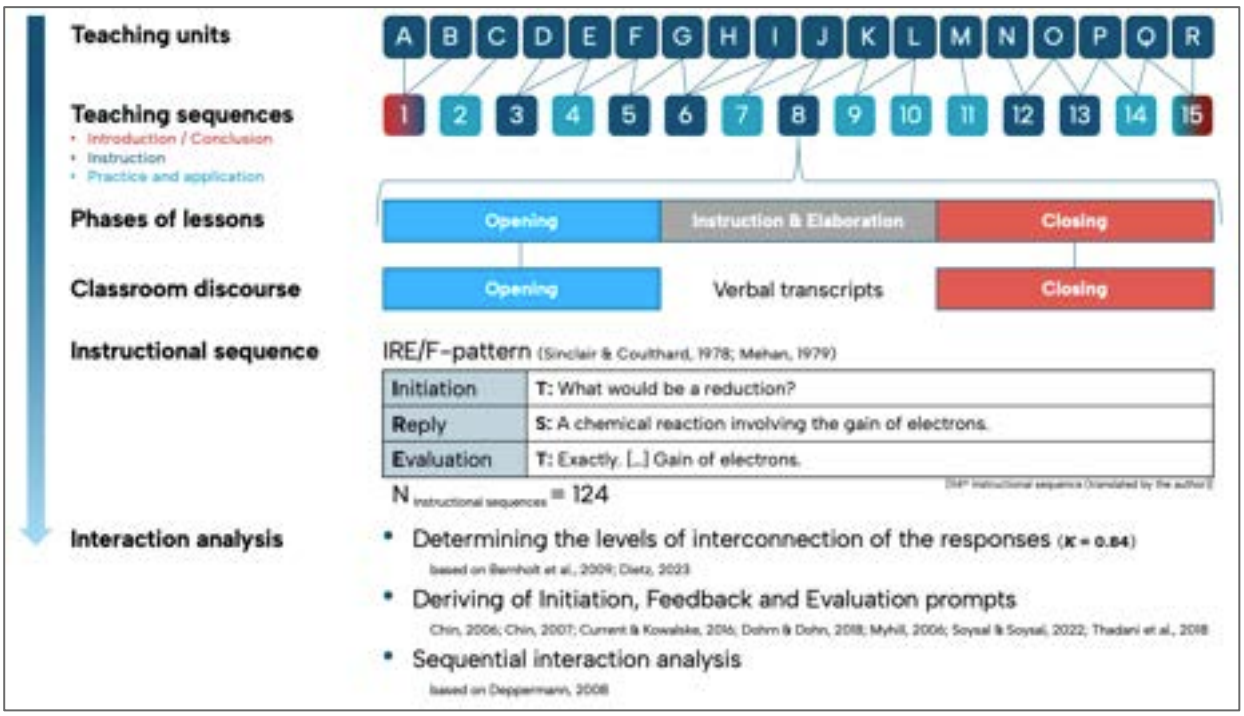
Methodology

A total of 18 lessons, each lasting 45 minutes, were recorded using a two-camera setup. One camera was positioned at the back of the classroom, capturing the teacher and the blackboard, while a second camera was placed at the front of the classroom, focusing on the students. To further enhance the quality of the recorded verbal interactions, the teacher was additionally equipped with a portable audio recorder.

To identify the relevant classroom interactions for analysis, the audio material was systematically pre-structured. First, the 18 recorded lessons were condensed into 15 teaching sequences (Figure 1), representing either the introduction or conclusion of the teaching unit, the development of new subject matter, or the practice and application of previously introduced content. Within these teaching sequencies, the instructional phases of introduction (opening), development (instruction and elaboration), and consolidation (closing) were subsequently identified.

Public classroom discourse initiated by the teacher, occurring primarily during the opening and closing phases, was transcribed. The resulting transcripts were then summarised and segmented into instructional sequences derived from observed interactions and individual utterances. Each instructional sequence constitutes a self-contained unit of content and follows the Initiation–

Figure 1. Data Preparation and Analysis Procedure.



Response–Evaluation/Feedback (IRE/IRF) pattern (cf. Sinclair & Coulthard, 1978; Mehan, 1979).

Figure 1 illustrates an exemplary instructional sequence in which the teacher initiates the interaction with a question, the student provides a response, and the teacher evaluates the response, thereby concluding the sequence. In case of inappropriate or incorrect responses, instructional sequences may be extended through a feedback prompt. In total, $N = 124$ instructional sequences were included in the analysis.

Subsequently, the levels of interconnection present in students' responses were determined. Five distinct levels of interconnection were identified (cf. Bernholt et al., 2009; Dietz, 2023) and grouped into three superordinate blocks. The first block comprises additive knowledge acquisition and includes the two lowest levels: experiential knowledge (Level 1) and factual knowledge (Level 2). Experiential knowledge refers to knowledge derived from students' everyday experiences and their encounters in chemistry lessons (e.g. observing experiments), whereas factual knowledge involves the identification of subject-relevant aspects, technical

Table 1. Category System – Levels of Interconnection Including Selected Examples.

Levels of Interconnection based on Bernholt et al., 2009; Dietz, 2023; (κ = 0.84)		Selected examples
II. Interconnecting to higher-level concepts (core ideas)	Abstraction	T: [...] I simply put it out there that, when a battery is used, chemical energy is converted into electrical energy. For this reason, batteries are also referred to as energy converters. Do you have an idea of what this means? **What does it mean that chemical energy is converted into electrical energy?** S: I'm not completely sure. But chemical energy is when there is a reaction or something like that, and energy is produced. That is **chemical energy to begin with, and then [...] transforming it or using it in such a way that it can be used as electrical energy.** T: Chemical energy has already come up in many other examples. If you think back, for instance, to combustion reactions, we described these as exothermic reactions. In such reactions, chemical energy that is stored in substances is released during a chemical reaction, for example in the form of light and thermal energy. And here we basically have the same situation. In this case as well, chemical energy is stored in a compound, and during a redox reaction it is released in the form of electrical energy [...] – **Abstraction: Energy conversion** [70th instructional sequence (translated by the author)]
I. Interconnecting within the topic	Justified relations	
	Unjustified relations	
0. Additive knowledge acquisition	Factual knowledge	T: [...] **What is reduction?** S: The release of– (T slightly shakes their head) – **the gain of electrons.** T: The gain of electrons, that's right. – **Factual knowledge: Definition** [37th instructional sequence (translated by the author)]
	Experiential knowledge	

terms, or definitions. The second block, interconnection within the topic, consists of two levels, differentiated by whether interconnections are established without justification (Level 3) or with explicit justification (Level 4). The highest level of interconnection is represented by abstraction (Level 5), in which interconnections are established by linking subject-specific content to higher-order concepts. An overview of the levels of interconnection is provided in Table 1.

To assess inter-rater reliability for the high-inferential category system used to classify levels of interconnection in students' responses, 40% of the instructional sequences were independently coded by two raters. This procedure yielded a Cohen's kappa coefficient of $\kappa = 0.84$, indicating almost perfect agreement according to the criteria proposed by Landis and Koch (1977). After the levels of interconnection in students' responses had been established, the methodological approach was extended to include sequential interaction analysis (cf. Deppermann, 2008). Within this analytical framework, initiation, feedback, and evaluation prompts were identified and categorised using a combined deductive-inductive approach (cf. Chin, 2006; Chin, 2007; Current & Kowalske, 2016; Dohrn & Dohn, 2018; Myhill, 2006; Soysal & Soysal, 2022; Thadani et al., 2018).

Results And Discussion

This section presents and discusses the results of the analysis of classroom discourse, with a particular focus on the relationship between initiation prompts, interaction patterns, and the levels of interconnection observed in students' responses. Special attention is paid to the role of evaluation and feedback prompts in shaping instructional sequences and influencing opportunities for cognitive engagement.

Initiation Prompts And Levels Of Interconnection In Students' Responses

The initiation prompts identified during the classroom discourse are presented in the left-hand column of Table 2. For analytical purposes, the levels of interconnection in students' responses were plotted against the respective initiation prompts. Two central aspects emerged from this analysis. First, 57% of the instructional sequences begin with the initiation prompts *name* or *describe*. These prompts predominantly elicit student responses at lower levels of interconnection. In contrast, 10% of the instructional sequences are initiated with the prompt *assume,* and 15% begin with *explain*. Responses following these prompts tend to reach higher levels of interconnection. This pattern suggests that such initiation prompts cognitively stimulate students to engage in more complex reasoning processes, which is consistent with the hierarchical organisation of cognitive processes described in Bloom's taxonomy (cf. Anderson & Krathwohl, 2001).

Table 2. Initiation Prompt and Resulting Level of Interconnection of Student Response.

Level of Interconnection / Initiation Prompts (N instructional sequences = 124)	Experiential knowledge	Factual Knowledge	Unjustified relations	Justified relations	Abstraction	Proportional Initiation Prompts
Name	11%	65%	16%	8%	0%	30%
Describe	35%	18%	35%	12%	0%	27%
Formulate (reaction equation)	0%	7%	86%	7%	0%	11%
Assume	15%	38%	31%	8%	8%	10%
Compare	0%	0%	100%	0%	0%	1%
Justify	0%	25%	0%	75%	0%	3%
Explain	11%	16%	32%	32%	11%	15%
Cognitive Conflict	0%	0%	100%	0%	0%	1%
Evaluate	0%	0%	0%	0%	100%	1%

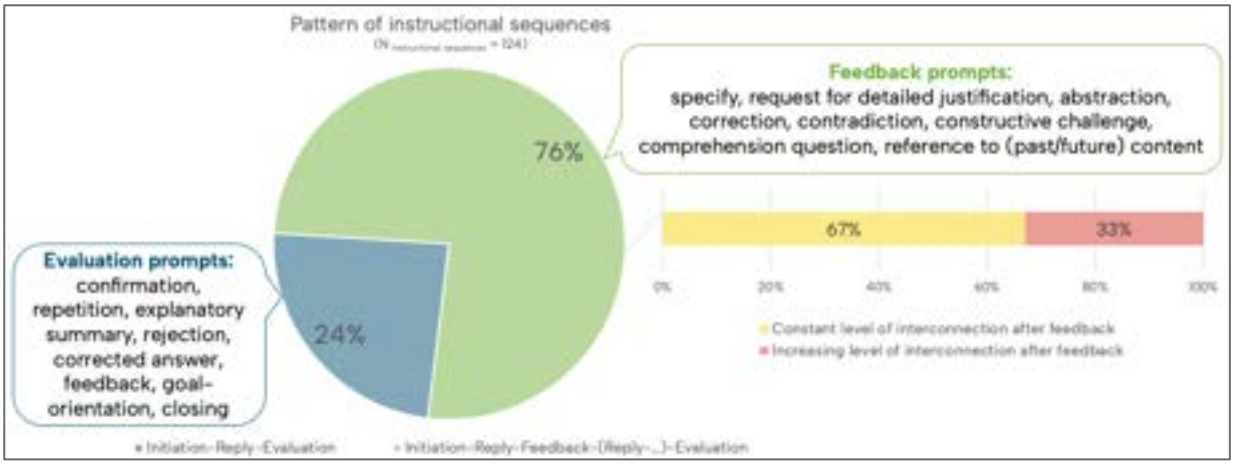
Second, the results indicate that initiation prompts are systematically associated with specific levels of interconnection. Prompts such as *name* and *describe* primarily address the reproduction of knowledge, whereas prompts such as *explain* are more likely to elicit responses involving higher levels of interconnection. These findings can be interpreted in relation to additive forms of knowledge acquisition. Responses elicited by initiation prompts such as *name* and *describe* frequently focus on the identification of technical terms, definitions, or concepts and therefore reflect additive knowledge building. Such forms of knowledge acquisition may constitute a necessary foundation for subsequent interconnection, as newly introduced subject matter can only be meaningfully related to prior knowledge once it has been explicitly established.

Interaction Patterns: Evaluation And Feedback Prompts

While the previous section focused on initiation prompts and the resulting levels of interconnection in students' responses, classroom interactions are not limited to initiation-response sequences. Rather, they are further shaped by evaluation and feedback prompts, which influence whether instructional sequences are concluded or extended. The following section therefore examines interaction patterns with a particular focus on evaluation and feedback prompts.

Overall, 24% of the instructional sequences follow the three-step Initiation–Response–Evaluation (IRE) pattern (cf. Mehan, 1979), in which the interaction is concluded through a content-related evaluation by the teacher. The evaluation prompts, derived using a combined deductive-inductive approach, are presented in Figure 2.

Figure 2. Proportion of Interaction Patterns, Derived Evaluation and Feedback Prompts, and Achieved Level of Interconnection of Student's Response after Feedback Prompt.



As evaluation prompts bring an instructional sequence to a content-related conclusion and classroom discourse subsequently continues with a new initiation prompt, they may restrict students' ongoing cognitive processes by prematurely terminating the interaction. As a result, opportunities for in-depth engagement with specific content or for further interconnection of subject matter may remain unexploited at particular points in the classroom discourse (cf. Chin, 2007).

In contrast, feedback prompts serve to extend instructional sequences and sustain students' cognitive engagement. When a discrepancy arises between the initiation and the student response, that is, when the response does not meet the expectations implied by the initiation prompt, a feedback prompt is formulated (cf. Naujok et al., 2008). The analysis shows that in 76% of the instructional sequences, interactions are extended through such feedback prompts. Within this framework, students may be asked to specify their response, provide a more detailed explanation, or correct their answer (cf. Chin, 2006). The specific functions of feedback prompts in relation to levels of interconnection are examined in the following section.

Regulative And Elaborative Functions Of Feedback Prompts

An analysis of the levels of interconnection following feedback prompts shows that in 67% of the instructional sequences, the level of interconnection in students' responses remains unchanged. This pattern indicates that feedback prompts predominantly serve to maintain or regulate the level of interconnection established by the initiation prompt, suggesting that initiation prompts largely shape the level of interconnection across an entire instructional sequence.

Within instructional sequences characterised by stable levels of interconnection, feedback primarily fulfils a regulative function by re-establishing symmetry between initiation and response when the initial student response does not align with the expectations implied by the initiation prompt. This form of feedback often involves requests for specification or clarification and supports subject-specific elaboration through the concretisation or expansion of students' responses. The findings suggest that instructional sequences maintaining a stable level of interconnection may nevertheless allow for substantial depth of content, as elaboration and differentiation can occur within a given level rather than necessarily through a transition to a higher level of interconnection.

In the remaining 33% of instructional sequences, feedback prompts are associated with an increase in the level of interconnection in students' responses. This tendency is particularly evident when follow-up questions prompt students to justify, explain, or further elaborate on their initial responses, thereby enabling longer and more complex contributions (cf. Chin, 2006).

Implications And Outlook

The findings of this study have several implications for both the analysis and the design of instructional interaction, as they provide a more fine-grained understanding of how the curricular demand for cognitively activating and interconnection-oriented instruction can be realised through classroom discourse. First, the results underscore the central role of initiation prompts in shaping the level of interconnection across instructional sequences. Initiation prompts such as *name* or *describe* tend to elicit reproductive forms of knowledge. However, rather than indicating superficial engagement, such responses may reflect additive forms of knowledge acquisition, in which technical terms, definitions, and basic concepts are made explicit. This additive knowledge building can be understood as a necessary foundation for subsequent interconnection, as newly introduced subject matter must first be established before it can be meaningfully linked to prior knowledge and integrated into more complex knowledge structures. In contrast prompts that inviting explanation or assumption are more likely to stimulate responses involving higher levels of interconnection. Taken together, these findings suggest that the deliberate formulation of open-ended initiation prompts can support a transition from additive to more cumulative and interconnected forms of knowledge construction over the course of instructional sequences, thereby facilitating the integration of new subject matter into existing knowledge structures (cf. Bernholt et al., 2020; Chin, 2006).

Second, the analysis highlights the differentiated role of evaluation and feedback prompts in shaping instructional interaction. Evaluation prompts tend to conclude instructional sequences and may limit opportunities for sustained cognitive engagement by prematurely terminating ongoing thinking processes. Feedback prompts, by contrast, can be productively integrated into instructional sequences to regulate the alignment between initiation and response and to encourage students to expand, clarify, or justify their contributions. Feedback thus fulfils both regulative and elaborative functions, supporting subject-specific depth of content and, in some cases, facilitating higher levels of interconnection within classroom discourse.

From a methodological perspective, the study demonstrates the value of combining an analysis of levels of interconnection with sequential interaction analysis, as this approach enables a differentiated examination of both cognitive and interactional dimensions of classroom discourse. Building on the present macro-analytical perspective, future research will move towards a fine-grained micro-analysis of classroom interaction. This next step will focus on the detailed examination of the content and structure of interactional sequences, with particular attention to the reconstruction and analysis of students' utterances. Such a micro-analytical approach aims to investigate how students' contributions are interactionally shaped and cognitively activated within instructional sequences and how these processes contribute to the development of a vertically interconnected subject matter understanding. By systematically linking interactional structures with the content-related development of students' reasoning, future research seek to further specify how classroom discourse can support both cognitive activation and the progressive interconnection of subject-specific knowledge.

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Inclusive Science Education: Interest In Experimenting And Perceived Self-Efficacy In An Interdisciplinary Teaching Concept

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As a design-based research project, the E²piMINT team developed and evaluated an inclusive and interdisciplinary teaching concept for lower secondary schools to promote interest in science and to provide teachers with effective support for lesson planning. Facilitating the cooperation between science education and inclusive education, the project brings together researchers from different fields: subject specific education in physics, biology and chemistry, as well as special education. A core aim of the project is to enable pupils with and without special educational needs (SEN) to learn effectively together through a hands-on teaching approach. Pupils work in groups at learning stations using "Researcher Boxes" to conduct experiments on different topics from the perspective of the three sciences subjects. Two project days on the topics of "colours" and "glueing and sticking" were designed and implemented in the teaching laboratories at the Goethe University Frankfurt with mixed prior ability classes. This first phase was followed by a second phase focusing on the applicability of the concept in school practice. Throughout the study, quantitative and qualitative methods (mixed methods approach) were used to analyse several constructs, such as learners' interest in experimenting as well as perceived experimental self-efficacy in a pre-post-follow-up design. This paper outlines the key features of the teaching materials and presents some preliminary results of the quantitative analysis.

Keywords: Inclusive Education, Interest, Self-Efficacy

Introduction

Context And Relevance To Science Education

In recent decades, and particularly since the ratification of the UN Convention on the Rights of Persons with Disabilities in 2009, the German school system has undergone many changes regarding the education of pupils with special educational needs (SEN). During this period, the proportion of pupils with SEN attending regular schools rather than special needs schools (i. e. specifically for pupils with SEN) has increased from 19.8% to 44% in 2020 (Kultusministerkonferenz, 2022). Therefore, there is a need to support this development and the teachers' pedagogical planning with tailored, research-based practical advice. An important challenge for didactic research is to provide teaching formats that enable students with diverse learning needs to work together. Finding a balance between individualised and collective teaching methods is essential in order to allow "learning on the common object" (Feuser, 1982). This standard has yet to be sufficiently achieved in practice. One reason for this can be found in the rare cooperation between science education and special education (Menthe & Hoffmann, 2015; Stinken-Rösner et al., 2020).

Research Framework

The design-based research project E²piMINT fits into this scenario, bringing together researchers from subject specific education in physics, biology and chemistry, as well as special education to develop innovative and inclusive teaching concepts for the secondary school level. The design-based research approach is an effective and flexible combination of theoretical and practical methods, allowing to test the effectiveness of the pedagogical approach during its development

(DBR Collective, 2003; Wilhelm & Hopf, 2014). The project ran from August 2022 to July 2025. During this time, a teaching concept based on existing research, empirical observations and dialogue with teachers from all types of schools was developed. This concept was implemented and tested through practical learning activities in teaching laboratories at the Goethe University and in schools in Frankfurt (Germany) and the surrounding area.

Research Aims And Target Group

One of the project's many challenges is to make interdisciplinary scientific content accessible to all learners, overcoming learning barriers and providing equal support. The project aims to design and produce teaching materials that can be used as directly and flexibly as possible in schools, while also contributing to research in inclusive science education. The effectiveness of the developed teaching concept was tested by evaluating, for example, students' interest in experimenting and perceived experimental self-efficacy, as well as their understanding of the scientific phenomena covered. The project's target group is students in lower secondary level across all school types. The focus is on pupils with SEN, particularly those with learning difficulties, in both regular and special schools. Comprehensive schools ("Gesamtschulen" in German) are of particular interest to the project due to their organisation and purpose. In fact, students at these schools participate in mixed-ability classes and often work using a project-based learning approach, which facilitates the implementation of the collaborative laboratory activities developed in the project.

Method

Research Methods

Table 1: Sample items of the questionnaire.

Scale	Sample Items
Interest in experimenting	*Experiments are boring.*
	I like to carry out set experiments independently.
Perceived experimental self-efficacy	*I can carry out an experiment on my own, without help, using the instructions.*
	I can do experiments even when I'm nervous.

A mixed methods approach combining quantitative and qualitative research methods was used throughout the study. With a questionnaire within a pre-post-follow-up design, the instrument included scales examining how interest in experimenting and perceived experimental self-efficacy changed among learners. The items were adapted to a simplified language given the presence of learners with SEN and were based on validated research instruments. The questionnaire was successfully piloted and adjusted (Fechner, 2009; Hoffman et al., 1998; Schroedter & Körner, 2012; Pantiri et al., 2024a). The final version of the questionnaire consists of eight items related to interest in experimenting and seven items related to perceived experimental self-efficacy, all of which are answered using a five-point Likert scale (from "strongly disagree" to "strongly agree"). To help children with reading difficulties, the Likert scale also included a visual component in the form of a one-to-five-star rating system, similar to those commonly used for reviews. Table 1 shows some examples of items for the two scales, validated in German. English translations are provided as an indication.

The pre-test occurred approximately three weeks before the students participated in the activity; the post-test took place immediately afterwards; and the follow-up test took place approximately

four to six weeks later. Semi-structured group interviews with learners and group observations were used as qualitative research instruments to further investigate their interest, group dynamics and learners' understanding. Given the central role of teachers in the project, their feedback was obtained using a semi-open questionnaire to assess their perspective on the effectiveness of the teaching approach and its applicability in school practice. Analysis of their feedback revealed that the teachers had a high appreciation of the concept, with particular emphasis on the successful alternation of individual and collaborative work, as well as the choice of experiments and materials, which were close to the students' everyday experience. However, this paper focuses on the quantitative results, so the qualitative research is not discussed in detail.

Study Design

In the first research phase, the developed concept was tested and evaluated under controlled conditions in the teaching laboratories at Goethe University Frankfurt (Pantiri et al., 2024b). This was followed by a second research phase in which the effectiveness of the concept was tested in school practice in cooperation with secondary school teachers. The concept is structured as station-based learning, with each station represented by a "Researcher Box", a practical kit containing the necessary materials for the experiments. This allows learners, divided into heterogeneous groups, to work as independently as possible during the experimental phase, helping and supporting each other within their own group, and, in a second phase, between groups. This concept was tested and optimised in design-based research cycles during the 2022/23 school year. Some key features emerged and became established during this time: a) using highly action-oriented and interdisciplinary experiments from physics, biology and chemistry, b) alternating individual and group work phases, c) valuing learner diversity by offering different approaches to the experiments as well as written and video instructions, help cards and additional tasks, d) using alternative methods of fixing and presenting results in the form of collaborative posters.

Two topics were chosen for the activities: "Colours" for grades 5th to 6th and "Glueing and Sticking" for grades 7th to 10th to investigate possible topic-related dependencies. Two sets of seven boxes have been developed for each topic. The "Colours" topic was tested and evaluated in the Goethe University's teaching laboratories in the 2023/24 school year, while the "Glueing and Sticking" topic was tested during the 2024/25 school year. The boxes for both topics were subsequently lent to schools, where teachers could use them flexibly in terms of duration and organisation, but without changing the aforementioned key features. The main study consists of different survey phases, depending on the location of the intervention (at the university or in schools) and on the topic of the activity, as shown in Table 2. These phases are analysed both individually and in relation to each other in the main study. The results presented in this paper focus on the implementation of the activities in the teaching laboratories at the university (Phase 1 and 2).

Table 2: Research design of the main study.

Phase 1 – Sample 1	**Phase 2 – Sample 2**	Phase 3 – Sample 3	Phase 4 – Sample 4
Teaching laboratories (university)		School practice	
Colours	**Glueing and sticking**	Colours	Glueing and sticking
11/2023-04/2024	***11/2024-02/2025***	*06/2024-07/2025*	*03/2025-07/2025*
Age 10-12	***Age 13-16***	*Age 10-12*	*Age 13-16*

Results

This section focuses on the preliminary quantitative results of Phases 1 and 2 (see Table 2), which were obtained by analysing the questionnaire described in the "Research Methods" section. The central research question for this analysis is: Do the activities "Colours" and "Glueing and Sticking" have an influence on students' interest in experimenting and on their perceived experimental self-efficacy? To investigate this question, a one-way analysis of variance (ANOVA) with repeated measures for dependent samples was performed on the quantitative data collected of each topic. In this analysis, time is the only ANOVA-factor: t1 stands for the pre-test, t2 for the post-test and t3 for the follow-up test. The intervention is the laboratory activity. Figure 1 and Figure 2 show the overall data distributions of the two scales per time point in the form of violin and box plots. Figure 1 shows the data for Phase 1 (activity "Colours"), and Figure 2 shows the data for the Phase 2 (activity "Glueing and Sticking"). The significance values and effect sizes resulting from the pairwise comparison (Bonferroni correction) are shown in Table 2 and 3, respectively.

Regarding the topic of "Colours", the median of the interest scale (Figure 1, left) increases from before the laboratory visit ("SL") to after the visit, and decreases again after 4-6 weeks. Both changes are significant, as showed in Table 3. The p-values are in fact <0.05 in both cases (t1 to t2 and t2 to t3) and the effect sizes of the increase and decrease are significant although small (0.2 < Cohen's d < 0.5), indicating a short-term increase of the interest in experimenting (Cohen, 1992). The median of the scale of perceived experimental self-efficacy (Figure 1, right) increases from before the school laboratory visit to after it and slightly decrease up to 4-6 weeks after the activity. The change from t1 to t2 is highly significant (p-value <0.001) with a medium effect size (Cohen's d >0.5), the decrease from t2 to t3 is only slightly significant, and the effect size is not significant at all (Cohen's d <0.2; Cohen, 1992). This indicates a possible score stabilisation up to 4-6 weeks after the activity.

Regarding the topic of "Glueing and Sticking", the median of the interest scale (Figure 2, left) does not increase, but rather decreases slightly over the three time points. However, these changes are not significant, as shown in Table 3, and the effect sizes are negligible. The median of the perceived experimental self-efficacy scale (Figure 2, right) increases slightly from t1 to t2, before decreasing to t3. These changes are also not significant, however, with negligible effect sizes.

Figure 1: Violin and box plots for the IE_EXP and SWE_EXP for the topic of "Colours". 5 corresponds to a high IE_EXP or a high SWE_EXP, 1 to a low one. The sample consists of the same N = 194 pupils in both scales.

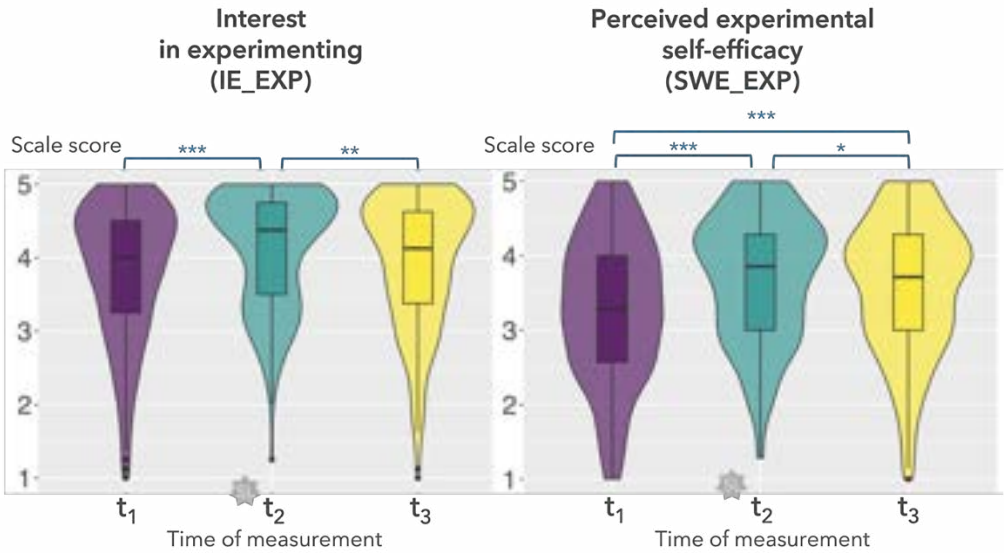


Table 3: Pairwise comparison of the two scales for the topic of "Colours": significance and effect size.

Scale	Time		Significance	Cohens d	Effect size
IE_EXP	t_1	t_2	p<0.001	0.36	small
	t_1	t_3	n.s.	0.14	-
	t_2	t_3	p<0.01	0.25	small
SWE_EX	t_1	t_2	p<0.001	0.51	medium
	t_1	t_3	p<0.001	0.32	small
	t_2	t_3	p<0.05	0.18	-

Figure 2: Violin and box plots for the IE_EXP and SWE_EXP for the topic of "Glueing and Sticking". 5 corresponds to a high IE_EXP or a high SWE_EXP, 1 to a low one. The sample consists of the same N = 142 pupils in both scales.

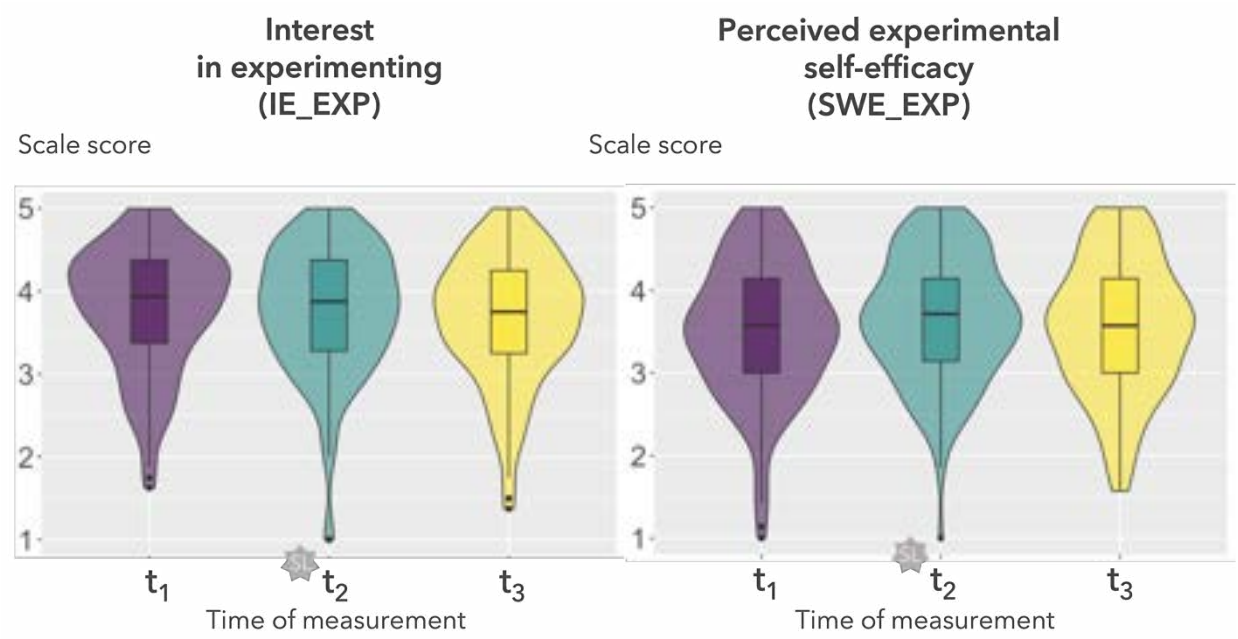


Table 4: Pairwise comparison of the two scales for the topic of "Glueing and Sticking": significance and effect size.

Scale	Time		Significance	Cohens d	Effect size
IE_EXP	t_1	t_2	n.s.	0.04	negligible
	t_1	t_3	n.s.	0.19	negligible
	t_2	t_3	n.s.	0.18	negligible
SWE_EX	t_1	t_2	n.s.	0.19	negligible
	t_1	t_3	n.s.	0.05	negligible
	t_2	t_3	n.s.	0.19	negligible

Discussion of Results and Implications

In summary, these preliminary results show different effects of the two activities. For the topic "Colours", the results suggest a short-term increase in students' interest in experimenting and a possible long-term increase of their perceived experimental self-efficacy. The increase in interest in the post-test results could indicate a positive perception of the laboratory activity "Colours"

and the pedagogical approach about experimenting on which the activity is based. The short-term increase in interest aligns to findings on the effectiveness of a one-off visit to a teaching laboratory (e. g. Pawek, 2009). Regarding perceived experimental self-efficacy, the medium effect size in its short-term increase, despite resulting in a small long-term effect, could suggest an interesting consequence of the intervention, and requires further investigation. To this extent, external factors may have influenced the perceived self-efficacy. Did lessons at school after the visit have any influence? Did the teachers themselves gain self-efficacy in conducting experiments with the class? Were the lessons between the intervention and the follow-up test more experimental or more theoretical? Ongoing additional analyses are therefore investigating the presence of these and other influencing factors, such as the emergence of subgroups in the sample, e. g., gender differences, belonging to a class or type of school, etc.

These results and the related discussion do not apply to the topic of "Glueing and Sticking", for which no significant changes were observed. Further research is needed to better understand these results. One plausible hypothesis for the lack of increase in interest in experimenting and perceived experimental self-efficacy is the difference in participants' age. In fact, as shown in Table 1, the pupils who worked on this topic were aged between 13 and 16 (grades 7th to 10th), while the pupils who worked on the topic of "Colours" were aged between 10 and 12 (grades 5th to 6th). Many studies (see, for example, Habig et al., 2025 for a systematic review) suggest a general decrease in interest in science and science-related topics as age increases. One way to test this hypothesis would be to adapt the "Glueing and Sticking" activity for younger age groups, enabling samples of similar ages to be compared and the topic variable to be better isolated. Another possibility emerges from comparing the results of quantitative and qualitative research analyses. In fact, as mentioned in the "Research Methods" section, semi-structured interviews were conducted with pupils who participated in the activities. An ongoing qualitative content analysis of these interviews investigates possible reasons for growth or lack of growth in the students' interest and perceived self-efficacy.

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Making Room Or Falling Into A Trap – Biology Teachers' Conceptions Of Evolutionary Lesson Planning

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From a constructivist perspective, learning environments that address students' conceptions are essential for meaningful learning. The Model of Educational Reconstruction (MER) provides a framework for developing conception-oriented biology instruction by systematically relating students' and scientific conceptions. While the MER has proven effective for designing instructional guidelines and interventions, little is known about how it is reflected in teachers' everyday lesson planning. Semi-structured interviews were conducted with experienced biology teachers (N = 9) focusing on lesson planning for evolutionary adaptation. Data were analyzed using qualitative content analysis combined with systematic metaphor analysis. We examine (1) teachers' conceptions of lesson planning and (2) their conceptions of students' conceptions of evolution. The results reveal contrasting teacher perspectives: while Mrs. Lilly understands students' conceptions both as learning difficulties that need to be addressed and as opportunities for learning, Mrs. Rose primarily views students' conceptions as obstacles to achieving curricular goals. These differences are reflected in distinct metaphorical framings (making room vs. preventing students from falling into a trap) and vary in their alignment with core principles of the MER. The findings highlight that research on students' conceptions must be systematically connected to teachers' professional conceptions in order to inform classroom practice and teacher education.

Keywords: evolutionary theory, students' conceptions, teacher training

Introduction

From a constructivist perspective, creating learning environments addressing students' conceptions is required to foster meaningful learning (Gerstenmaier & Mandl, 1995; Schrenk et al., 2019). A key framework for this is the Model of Educational Reconstruction (MER; Duit et al., 2012), which allows the development of learning environments based on a systematic comparison of students' and scientific conceptions. The MER has proven effective in developing conception-orientated biology instruction on the level of guidelines (e.g. Weitzel, 2024; Kattmann, 2017) and learning interventions (e.g. Zabel & Gropengießer, 2011; Kattmann, 2017). Nevertheless, little is known about the use of the MER in everyday classroom contexts (Hamman & Asshoff, 2014). Additionally, there is limited research on how the MER can be adapted for the design of learning environments for teachers, such as teacher training programmes (Jelemenská, 2012; van Dijk & Kattmann, 2007).

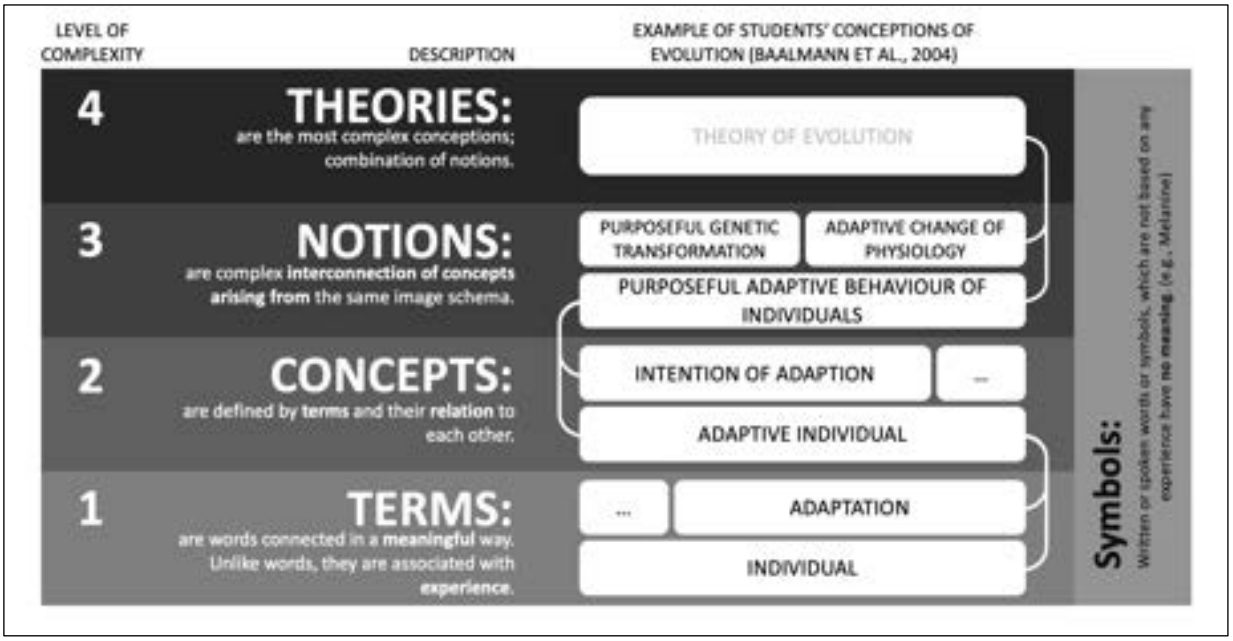
The findings of this study are intended to be used for the development of a professional teacher training program for German secondary school biology teachers, primarily focusing on teachers' individual conceptions of students' conceptions of evolution and their strategies of dealing with them in classroom. In this context, the MER has been adapted for use in teacher education. The theory of evolution was chosen as the biological context because it is characterized by a wide range of students' conceptions (Gregory, 2009; Harms & Reiss, 2019; Zabel & Gropengießer, 2011) causing persistent learning barriers. Furthermore, evolutionary theory plays a central role in understanding biology (Dobzhansky, 1973).

Theoretical Framework

Teaching And Learning Considering Learners' Conceptions

Research suggests that addressing learners' conceptions plays a key role in facilitating conceptual change (Duit & Treagust, 2003; Riemeier & Gropengießer, 2008; Shtulman et al., 2016). We understand conceptions as individual mental constructs. They can be viewed on different levels – ranging from terms and concepts to notions and theories – and differ from symbols (e.g., words), which lack an experiential foundation (see Figure 1).

Figure 1. Hierarchical order of conceptions on different levels of complexity (based on Michelsen et al., 2022) with examples on the topic of evolutional adaptation.



Using evolution as an example, an extensive body of research exists about students' conceptions, learning barriers and strategies that are specifically designed to foster conceptual change (e.g., Bishop & Anderson, 1990; Brumby, 1979; Harms & Fiedler, 2019; Weitzel, 2024; Zabel & Gropengießer, 2011). Despite this substantial research base, evidence from Hartelt et al. (2022) indicates that even practicing secondary school biology teachers struggle to address students' conceptions effectively.

Conceptual Metaphor Theory

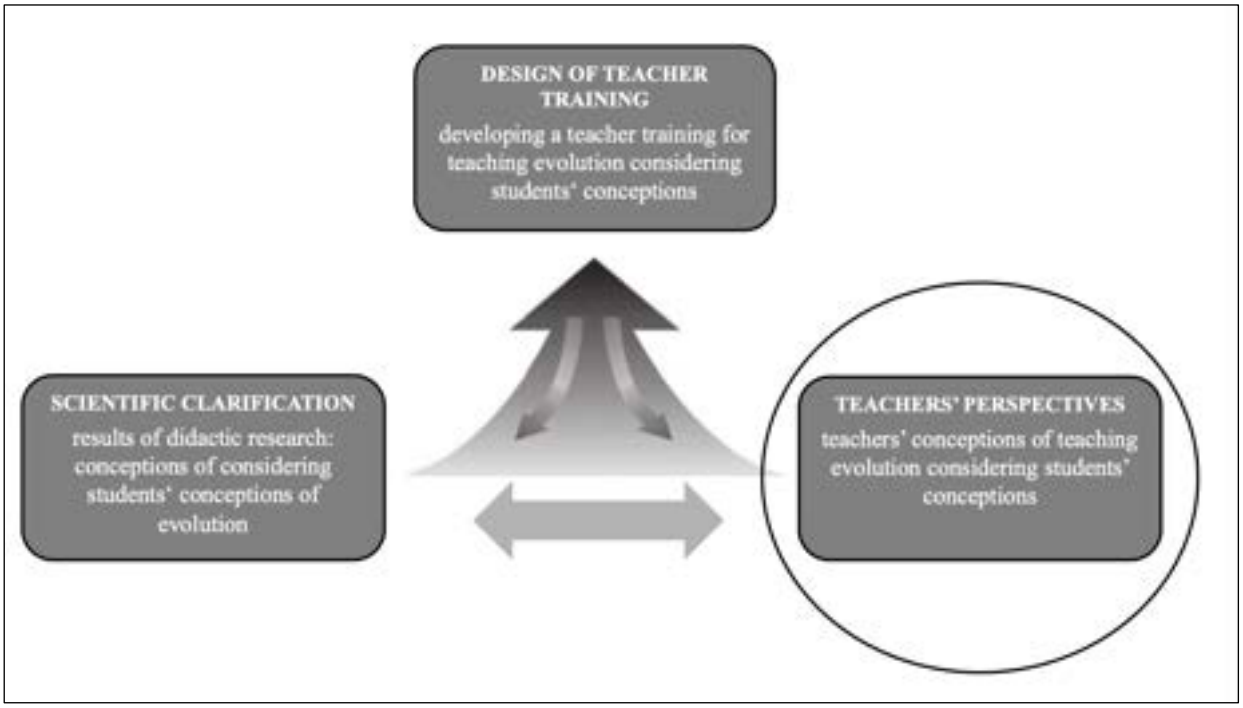
Conceptual Metaphor Theory (Lakoff & Johnson, 1980) conceptualizes metaphors as cognitive structures that shape human cognition. In order to make sense of abstract phenomena that are not directly accessible through experience, individuals draw on embodied source domains grounded in bodily and everyday experience (Niebert et al., 2012). Meaning is constructed by mapping these concrete, experience-based domains onto more abstract target domains. For example, evolutionary adaptation is often conceptualized through a goal-directed source–path–goal schema (Gropengießer & Groß, 2019), in which students draw on their experience of moving from a starting point toward a defined destination. This metaphorical framing can lead to interpretations of evolution as a purposeful and directed process, which contrasts with the scientific understanding of adaptation as an undirected population-level process. Considering students' conceptions is crucial in evolution education, as these pre-instructional concepts strongly influence how students make sense of evolutionary mechanisms and thus need to be addressed deliberately in lesson planning. For teachers, knowledge of these conceptions is essential for anticipating learning difficulties, selecting appropriate instructional strategies, and supporting students in developing scientifically accurate understandings. In this study, we examine teachers'

(metaphorical) framings in lesson planning to gain deeper insights into their conceptions of teaching evolution.

Study Framework

The aim of this project is to design a teacher training program that helps teachers adress students' conceptions of evolution, supports their professional development, and strengthens their ability to integrate these conceptions into biology instruction. To this end, we draw on the Model of Educational Reconstruction (Duit et al., 2012), adapted for teacher education (van Dijk & Kattmann, 2007) and further refined for the development of the proposed training program. This study concentrates on investigating teachers' perspectives (see Figure 2).

Figure 2. Study framework: The MER for teacher education, based on the ERTE-Model, developed by van Dijk & Kattmann (2007). The circular mark shows where to locate this study.



Research Questions

- Which conceptions of students' conceptions of evolution can be identified from teachers' lesson planning processes?
- Which conceptions of evolutionary lesson planning can be identified from teachers while planning processes?
- How can teachers' conceptions regarding students' conceptions of evolution be interpreted in the context of the Model of Educational Reconstruction?

Methods

We conducted semi-structured individual interviews with nine practicing biology teachers in Lower Saxony, Germany. Participants had experience teaching evolution and at least three years of general teaching experience. The sample was heterogeneous and included a teacher educator (N = 1), a teacher with a PhD in science education (N = 1), and a career changer with a PhD in biology (N = 1). The participation was voluntary.

The interviews comprised three parts:

1. Teaching evolution: experiences with teaching evolution, lesson planning approaches, and the use of a text on evolutionary adaptation.

2. Lesson planning: planning a lesson on evolutionary adaptation using antibiotic resistance, followed by presentation and explanation of instructional decisions.
3. Teaching and learning: views on teaching roles, learning processes, the consideration of students' conceptions and material selection in planning.

The data were examined using qualitative content analysis (Mayring, 2010) alongside systematic metaphor analysis (Schmitt, 2017).

Results

In order to answer our research questions, we focus on two deductively derived categories: *conceptions of lesson planning* and *concepts of students' conceptions of evolution* (see Table 1). Furthermore, our findings are illustrated using the examples from the interviews with Mrs. Lilly (Interview 8) and Mrs. Rose (Interview 9), both names are pseudonymized.

Table 1. Conceptions of the interviewed teachers Mrs. Lilly and Mrs. Rose regarding the main categories 'conceptions of lesson planning' and 'concepts of students' conceptions of evolution'.

No.	Conceptions of lesson planning	Concepts of students' conceptions of evolution
8 (Mrs. Lilly)	Anticipate students' steps of understanding Making room for students' conceptions	Cause for learning difficulties Chance for learning
9 (Mrs. Rose)	Anticipate students' steps of understanding	Obstacles for test performance Trap

Make Room: Mrs. Lilly

Mrs. Lilly structures her lesson planning using the source–path–goal schema. She describes students as "going through different steps of understanding", starting from "what happened in previous lessons". In this way, she supports students in reaching the "teaching goal – where I want them to go, which curricular competencies I want to address". In addition to the level of learning curricular competencies, Mrs. Lilly addresses the level of understanding evolution, in which students' conceptions "play a big role".

> I know that learners' conceptions of evolution differ significantly from what we see biologically. This means that when it comes to selection or evolutionary processes, we need to look at what conceptions the students already have. What are the learning difficulties we face in this area? Clearly, one of these is active adaptation. (Mrs. Lilly)

For Mrs. Lilly, students' conceptions are "part of every lesson. They are part of the lesson planning, part of the lesson I teach and part of my reflection on the lesson. I give them enough room in all three phases". Additionally, Mrs. Lilly actively diagnoses students' conceptions and encourages students to become aware of their own conceptions. As she states, students "want to learn something and while doing this they find out that reflecting their own conceptions is a part of their learning process". This suggests that she understands students' conceptions both as learning difficulties that need to be addressed, and a chance for students in order to better understand the theory of evolution.

Mrs. Lilly does not perceive the development of curricular competencies and the fostering of evolutionary understanding as incompatible. However, she acknowledges the challenge of addressing both levels simultaneously: "How can I continue my lesson in a way that gives space

to the conception while still achieving my instructional goal? I believe this is one of the most challenging aspects of teaching.

Prevent From Falling Into A Trap: Mrs. Rose

Mrs. Rose structures her lesson planning using the same experience-based referent as Mrs. Lilly, the source-path-goal schema. She also refers to "steps of understanding", and to a "goal orientation: when do I have to be where content-wise". When characterizing her teaching goal, she makes clear, that, in contrast to Mrs. Lilly, she prioritizes the level of learning curricular competencies over the level of fostering understanding of evolution in her lesson planning:

> How adaptations or characteristics change through selection in connection with mutations and random changes in characteristics – that is what they should learn in the basic principle. And once they have understood this, they should be able to complete the tasks in their high school graduation exams more or less successfully. So – that's the goal. So, I'm not talking about something you should internalize because it will make your life better. (Mrs. Rose)

Another major difference compared to Mrs. Lilly lies in Mrs. Rose's understanding of students' conceptions of evolution. She describes them as a "trap that many students fall into, they fall into that thinking pattern". Mrs. Rose characterizes these conceptions as students' "wrong ideas, based on everyday experiences" that she "correct[s] accurately". This suggests that she views students' conceptions primarily as obstacles to achieving teaching goals and exam success. Consequently, Mrs. Rose's views on students' conceptions of evolution lead to a selective consideration of them, depending on the significance for reaching the teaching goal. She reflects: "What happens in my lessons to prevent them from falling into that trap or speak this conception out loud? Or do I want to address the students' conception explicitly so that we can discuss what it actually means?"

Discussion

Mrs. Rose's and Mrs. Lilly's lesson planning processes reveal fundamentally different approaches to students' conceptions.

For Mrs. Lilly, two interconnected notions of planning evolutionary lessons can be identified. Her planning on the level of curricular competencies is structured by a source–path–goal schema. In her view, students' conceptions of evolution belong to a different but equally relevant level — the level of conceptual understanding of evolution. At this level, her lesson planning is metaphorically structured by the idea of *making room* for students' conceptions. The structure of the Model of Educational Reconstruction (MER) supports the diagnosis of students' conceptions, the development of learning environments that foster conceptual understanding, and the reflection of instruction using students' conceptual change as an indicator. This framework thus creates systematic opportunities to integrate students' conceptions into lesson planning. Mrs. Lilly's understanding of *making room* for students' conceptions is therefore consistent with the central principles of the MER.

In contrast, Mrs. Rose clearly prioritizes the level of curricular competency development over fostering a deeper conceptual understanding of evolution. She primarily interprets students' conceptions as obstacles that hinder students from reaching the teaching goal. Consequently, she tends to avoid engaging with students' conceptions, which she metaphorically frames as *traps*. Within this metaphorical framing, students appear unable to leave these traps once they have entered them, suggesting a rather static view of learning. Such conceptions are not compatible with the fundamental principles of the MER, as MER-based learning environments are designed

to support students in transforming their conceptions toward scientifically more adequate understandings.

These two cases illustrate how systematic metaphor analysis can provide deeper insights into teachers' cognitive structures underlying lesson planning. Moreover, the examples of Mrs. Lilly and Mrs. Rose demonstrate that successful conceptual change in classroom practice cannot be achieved by focusing solely on students and their conceptions. Greater attention must also be paid to the teacher level, particularly to how teachers interpret and address students' conceptions during lesson planning and instruction. If teachers' conceptions remain unexamined, research on students' conceptions risks remaining disconnected from instructional practice and therefore offers limited guidance for lesson planning and teaching decisions.

From a different, more cognitive perspective, the growth mindset (Dweck & Yeager, 2019) describes a similarly polarised approach to learning obstacles. On one side of the spectrum, learning obstacles are seen as a threat to the learning process and are therefore avoided. On the other side, learning obstacles are deliberately targeted by teachers, who see the irritation experienced by learners when confronted with them as a learning opportunity.

These different perspectives are particularly important for teacher training, as they could have a significant influence on the professional conduct of future teachers: remaining effective requires a controllable attribution of the causes of learning barriers. A study with math teachers (Copur-Gencturk et al., 2025) could show, teachers struggling with learning barriers in their lessons, attributed them to a lack of prior knowledge, a general inability for dealing with the subject or memory problems - causes which are mostly uncontrollable for a teacher. Their findings suggest that the ways teachers characterize common student struggles are linked to their instructional practices. The findings of the study presented here and the insights of Copur-Genturk et al. (2025) suggest that the investigation of teachers' conceptions of prominent learning barriers of evolution (Zabel & Gropengießer, 2011) should be the next step in the development of a teacher training programme in line with MER.

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Visualizing Chemistry: Analyzing Graph Usage In Textbooks And Its Implications For Teaching

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Graphs are central to science and chemistry education, representing abstract concepts and providing alternatives to purely text-based learning. However, their high information density and abstract nature can overwhelm students, potentially leading to cognitive overload. Developing graph competence, the ability to understand and use graphs meaningfully, is therefore essential. While research on graph use and comprehension is established in science education research, chemistry-specific insights remain limited. This study addresses that gap by introducing a graph competence model for chemistry and using it as an analytical lens in a systematic textbook analysis to gain a practice-orientated understanding of graph use in chemistry. Eight German lower- and upper-secondary chemistry textbooks were examined using a category-driven mixed-methods approach, identifying and analyzing 3,550 visual representations. The findings highlight domain-specific characteristics of graph types in chemistry and their distribution across content areas and educational levels, as well as distinct differences in the coverage of graph competence components in tasks between school levels and school types. These patterns point to potential challenges that students are likely to face when engaging with graphs in chemistry and extend previous research on graph use in science education by providing a focused chemistry education perspective. The conference paper introduces the graph competence model and presents selected results that focus on assigning graph related tasks to competence components and levels. Building on these findings, it derives concise implications for teaching graphs in chemistry and for future research on students' graph competence and graph-related difficulties.

Keywords: Graph Competence, Visual Representations, Textbook Analysis

Introduction

Graphs are pervasive in everyday life, science, education, and society. As abstract visual representations, they do not depict objects through direct similarity but through analogical relations between variables, typically with at least one continuous variable. Scales specify the range of possible values a variable can take, thereby enabling the description and interpretation of data based on its position along the axes. In contrast, in realistic pictures the relationship between an object and its representation is directly visible, creating a concrete structural correspondence that is constrained by the two-dimensional nature of the representation (Schnotz, 2001).

From an educational perspective, graphs have an ambivalent role. On the one hand, chemistry's inherently visual nature makes graphs ubiquitous: students encounter them frequently across various areas of chemistry education (Bowen & Roth, 2002; Ring & Brahm, 2020). They are important for visualizing and explaining data and concepts in both theoretical and experimental contexts (Boels et al., 2019; Bowen & Roth, 2002). Consequently, accurate reading, interpretation, and constructing of graphs are essential for acquiring chemistry specific-knowledge. The importance of engaging with graphs is also emphasized in curricula (e.g., Ministerium für Schule und Weiterbildung des Landes Nordrhein-Westfalen, 2022; National Research Council, 2013). On the other hand, prior science education research shows that graphs pose challenges for students due to their abstractness and complexity (Bowen & Roth, 2002; Glazer, 2011; Jahnke, 2020), and that understanding them is far from intuitive for learners (e.g., Ring & Oberrauch, 2024).

To address these difficulties and to realize the learning potential of graphs in chemistry education, graph competence is necessary. Graph competence is the cognitive ability to understand graphs and, based on this understanding, independently solve graph-related tasks involving both information extraction and graph construction (Lachmayer, 2008). Because graph competence is domain-specific, it is essential that learners develop chemistry-specific graph competence to engage meaningfully with graphs and to develop a multimodal understanding of chemical concepts. This competence is not only crucial from an educational point of view but also in students' everyday lives: they need it not only to understand graphs in contexts such as climate change or health statistics, but also to critically question and evaluate the data represented. Nevertheless, despite the importance of graphs in general and graph competence in particular, research on graph competence in chemistry education remains limited, especially with regard to the difficulties learners experience when working with graphs and how instruction can both address these difficulties and foster the learning potential of graphs.

Figure 1. Revised model of graph competence for chemistry (adapted from Lachmayer, 2008). English translations are primarily based on Bernholt and Parchmann (2011) and Von Kotzebue et al. (2015).

<table>
<tr><td></td><td colspan="3">Information extraction</td><td colspan="2">Construction</td></tr>
<tr><td></td><td rowspan="4">Identification</td><td colspan="2">Recognize the illustrated relation</td><td>Selecting the right graph type</td><td rowspan="5">Construction of the frame</td></tr>
<tr><td colspan="2" rowspan="2">Assignment/classification of the variables to the axes</td><td>Assigning the variables to their axes</td></tr>
<tr><td>Labelling the axes</td></tr>
<tr><td colspan="2">Assignment of the data series to the symbols (‘legends’)</td><td>Drawing the scale</td></tr>
<tr><td colspan="2">Note the scale range</td><td>Creating the legend</td></tr>
<tr><td rowspan="5">Formal dimension
Content dimension</td><td rowspan="2">Off-reading</td><td>Level 1</td><td>Identification of a function value</td><td>Plotting the data points</td><td rowspan="5">Data plotting</td></tr>
<tr><td>Level 2</td><td>Description of graphs</td><td rowspan="3"></td></tr>
<tr><td rowspan="3">Explanation and interpretation</td><td>Level 3</td><td>Domain-specific interpretation of a function value</td></tr>
<tr><td>Level 4</td><td>Domain-specific interpretation of one graph</td><td>Sketching a connecting line between the data points or free sketching a trend line</td></tr>
<tr><td>Level 5</td><td>Domain-specific interpretation of more than one graph</td><td>Freehand drawing of multiple trends</td></tr>
<tr><td colspan="6">Integration</td></tr>
</table>

Theoretical Framework

Graph competence in chemistry was conceptualized and operationalized on the basis of a model of graph competence originally developed for biology education (Lachmayer et al., 2007; Lachmayer, 2008). This model was then refined to account for chemistry-specific requirements, particularly the characteristics of typical chemistry tasks. It was further adapted using the "Model of Hierarchical Complexity" (Commons et al., 1998), as applied to chemistry by Bernholt et al. (2009). The resulting model shows that competent engagement with graphs involves three core components: "information extraction" from graphs, "construction" of graphs, and "integration" of texts and graphs. Each component is further divided into specific subcomponents. In this study, as these are most relevant to our research question, we focus on the component "information extraction" from graphs and on the newly developed subcomponents "off-reading" and "explanation and interpretation", which are differentiated into levels of increasing complexity (see Figure 1).

Furthermore, graph competence can be differentiated into a domain-general and a domain-specific dimension. These two dimensions are reflected in the graph competence model, where they appear in the respective levels of the component "information extraction" (see Figure 1). The domain-general dimension involves aspects related to the content-independent, formal dimension of graph competence. Since these aspects do not concern the underlying content of the graph, they are relevant across different subjects. This includes, for example, identifying a function value in a graph (level 1) and describing the graph's overall shape (level 2). In contrast, the domain-specific dimension comprises aspects that pertain to the underlying content represented by a graph. This includes, for example, subject-specific interpretations of a function value (level 3), of a single graph (level 4), and of multiple graphs (level 5). These aspects are therefore specific to graph competence within a particular subject domain, in this case chemistry. In this regard, integrated graph competence involves bringing together the formal and the content-related dimensions of graphs. The importance of this integration becomes particularly evident when students explain complex graphs, for example in the context of chemical equilibrium: on the one hand, they must understand the underlying chemical principles (e.g., that the concentrations of reactants and products remain constant at equilibrium), and on the other hand, they must recognize how these principles are represented formally in the graph (e.g., horizontal lines with a slope of zero). This differentiated perspective on graph competence underscores the necessity for students to develop graph competence that specifically reflects the particular characteristics and demands of graph use in chemistry.

Aim and Research Question

The research project aims to address the research gap (see above) by assessing students' graph competence in chemistry and by exploring ways to enhance it through targeted differentiation strategies.

To address the overarching research question, it is first necessary to gain foundational insights into the domain-specific use of graphs in chemistry. The textbook analysis presented in this conference paper serves this purpose and provides practical insights into how graphs are used in chemistry education. Textbooks were selected because they closely reflect the implemented curriculum (Khaddoor et al., 2017; Upahi & Ramnarain, 2019), and their analysis therefore offers valuable information about the content likely addressed during classroom instruction. Moreover, textbooks play a central role for both students, serving as learning resources that enable flexible, self-paced access to content and support individual learning (Chi et al., 2024; Rusek & Vojíř, 2019), and for teachers, functioning as tools for lesson planning and instruction as well as sources of subject-matter information (Meyer & Pietzner, 2022; Vojíř & Rusek, 2022). The main research

question guiding the textbook analysis is therefore: *How are graphs used in chemistry textbooks?* This overarching question is further specified by the following four sub-questions (SQs):

SQ1: *How frequently are graphs used compared to realistic pictures?*

SQ2: *What types of graphs are used?*

SQ3: *In which content areas are graphs most frequently used?*

SQ4: *To which competence components and competence levels do graph-related tasks (line graphs) correspond?*

The present conference paper focuses on SQ4, examining how graph-related tasks are linked to specific competence components and levels. A comprehensive presentation of all results, including findings related to SQ1–SQ3, is provided in Fichtner and Groß (2025a).

Methodology

To address the research question, a systematic coding approach was applied to eight chemistry textbooks, guided by a structured category scheme and informed by the method of graphical analysis (Slough et al., 2010; Khine & Liu, 2017). Building on this established approach, we developed an adapted graphical analysis procedure tailored to our research aim, enabling a systematic and structured analysis of both graphs and realistic pictures in the textbooks.

Eight German chemistry textbooks from North Rhine-Westphalia were selected, representing three major publishers (*Klett*, *Westermann*, and *C.C.Buchner*) and covering both lower and upper secondary education as well as two school types (middle schools, $N = 2$; grammar schools at lower secondary level, $N = 3$; grammar schools at upper secondary level, $N = 3$). One textbook per educational level was chosen from each publisher, allowing for meaningful comparisons across publishers and school types. Table 1 presents the analyzed textbooks by secondary level and school type, along with their abbreviations.

Table 1. Textbooks analyzed in the study, listed by secondary level and school type.

Secondary level, school type	**Name**
Lower secondary textbooks, grammar schools	*Elemente Chemie 7-10*, *Chemie Gesamtband Sekundarstufe I*, *Chemie heute*
Lower secondary textbooks, middle schools	*Prisma Chemie 1/2*, *Blickpunkt Chemie 7-10*
Upper secondary textbooks, grammar schools	*Elemente Chemie Oberstufe*, *Chemie Einführungsphase* (abbreviation: *Buchner H1*), *Chemie Qualifikationsphase* (abbreviation: *Buchner H2*), *Chemie heute SII*

Including textbooks from major publishers and across multiple school types and levels ensures that the sample is representative of materials widely used by chemistry teachers, thereby providing authentic insights into the use of graphs in educational contexts. The only exceptions are that *C.C.Buchner* currently does not publish a middle school textbook and that its upper secondary textbook is divided into two volumes (*Buchner H1* and *Buchner H2*), which were analyzed together to ensure comparability.

For the specific analysis of the textbooks, we first systematically identified 3,550 visual representations (including graphs, realistic pictures, and mixed forms that combine elements of both graphs and realistic pictures). These visual representations were then analyzed using a

category scheme. In the following, we present the part of the analysis that addresses SQ4 (for a full account, see Fichtner & Groß, 2025a).

Regarding SQ4, the graph competence model outlined above plays a crucial role, as it provides the analytical framework for examining the competence components and levels targeted by graph-related tasks and therefore constitutes a central part of the category system. To answer SQ4, we first distinguished between line graphs linked to tasks and those linked to texts (category "Text/Task Assignment"). Second, based on the identified graph-related tasks, we examined whether they aligned with the relevant main competence component, either "information extraction" or "construction". Third, we analyzed the tasks classified as information extraction tasks and coded them according to one of the five competence levels (see Figure 1). To ensure coding reliability, two researchers independently assigned competence levels to 20% of the line graph-related information extraction tasks (n = 74), compared and discussed any discrepancies, and, where necessary, refined the coding scheme, definitions, and examples (Guest et al., 2012; Kuckartz & Rädiker, 2022). Any remaining disagreements were resolved by a third rater using a consensus-based approach. Intercoder reliability, assessed using Cohen's Kappa, indicated a very high level of agreement (κ = 0.946; Balci, 2022; Cohen, 1960; Gamer et al., 2019; Landis & Koch, 1977; The jamovi project, 2024).

Findings

The results reveal clear differences in the number of graph-related tasks in textbooks depending on school type and educational level. Lower secondary middle school textbooks contain 28 line graphs and 31 associated tasks, corresponding to 1.11 tasks per line graph. In contrast, lower secondary grammar school textbooks include 86 line graphs accompanied by 140 tasks, corresponding to 1.63 tasks per line graph. A further increase appears at the upper secondary level, where 277 line graphs are linked to 513 tasks, resulting in 1.85 tasks per line graph. Thus, task density per line graph increases from lower secondary middle school to lower secondary grammar school textbooks and is highest in upper secondary grammar school textbooks. This pattern implies that learners at grammar schools, and especially at the upper secondary level, encounter line graphs more frequently and engage with them through more tasks than learners at middle schools. It suggests that upper secondary chemical content is particularly well suited to be represented in graph-based tasks and that students at this level are better able to engage with graphs without experiencing cognitive overload. This interpretation is consistent with previous research indicating that graph competence tends to increase with age and grade level (Curcio, 1987; Lachmayer, 2008; Padilla et al., 1986). However, it remains unclear whether students acquire a sufficient level of graph competence during lower secondary education to be adequately prepared for the higher task density in upper secondary textbooks, or whether they instead experience cognitive overload because their graph competence has not kept pace with the increased use of graph-related tasks. This issue is particularly critical for students who transfer from middle school to upper secondary grammar schools, as they have had comparatively few opportunities to develop graph competence through task engagement.

A closer look at the competence components addressed by line-graph tasks reveals a pattern in lower secondary grammar and middle school textbooks (see Figure 2). In both school types, tasks corresponding to the competence component "construction" occur slightly more often than tasks assigned to the competence component "information extraction". This suggests that, at this educational level, graphs are frequently used to support scientific working processes, for example, in the context of experiments. Yet the difference between the two components is small, indicating that both school types foster graph competence that addresses both the construction of

graphs and the extraction of information from them in a comparable way. In upper secondary education, however, this ratio changes, and a shift toward more frequent use of graph-related tasks associated with the competence component "information extraction" becomes apparent (see Figure 2). The focus of the tasks thus narrows, with students increasingly required to extract information from given graphs. A possible explanation is that students in upper secondary education possess more advanced subject-matter knowledge, which enables them to interpret graphs in greater depth regarding the underlying chemical concepts. In addition, this pattern supports the assumption that chemical content at this level is particularly well suited to graphical representation, thereby further encouraging an emphasis on information-extraction tasks.

Figure 2. Percentage distribution of main competence components in graph-related tasks by school type. Percentages represent the proportion of each competence component relative to the total number of competence components within each school type. One unclassifiable graph from lower secondary education (grammar school) is excluded from this visualization.

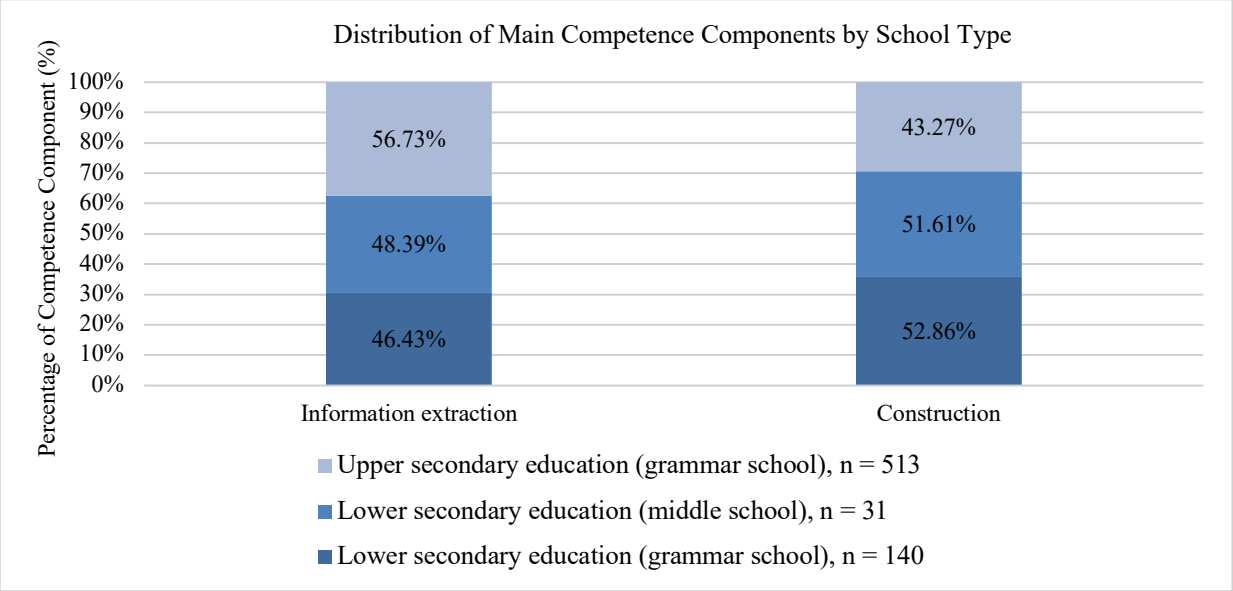
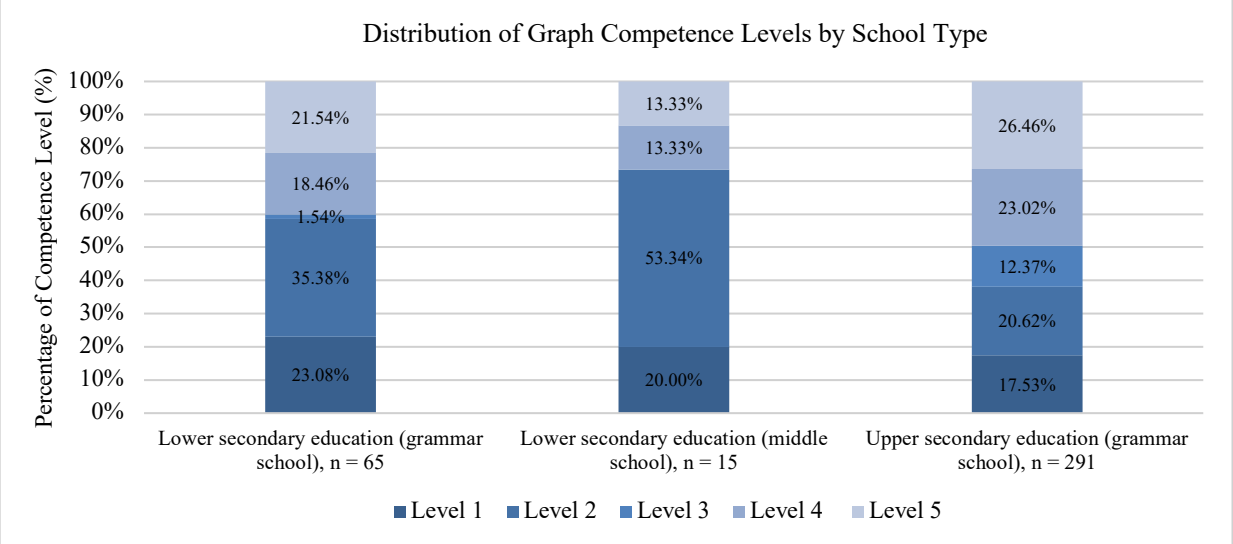


Figure 3. Percentage distribution of graph-related tasks by competence level and school type. Percentages indicate the proportion of tasks within each competence level relative to the total number of tasks analyzed for each school type.



Considering the competence levels within the competence component “information extraction”, learners across all school types encounter tasks that span multiple levels of graph competence and thus demand a range of different cognitive processes (see Figure 3).

Moreover, the discrepancy between school types and educational levels described above becomes more pronounced when the competence levels are considered. In lower secondary middle school textbooks, tasks at level 2 – requiring students to describe graphs – occur most frequently (53.34%), whereas tasks from the other competence levels are comparatively rare. A similar pattern emerges in lower secondary grammar school textbooks, where level 2 tasks also dominate (35.38%), but tasks from the remaining levels appear noticeably more often than in middle school textbooks. In terms of the dimensions of graph competence outlined in the theoretical framework, this indicates a clear emphasis on tasks that address the formal, content-independent dimension in lower secondary education textbooks. In contrast, upper secondary grammar school textbooks exhibit a different pattern, with graph-related tasks distributed more evenly across competence levels, thereby addressing the full range of cognitive demands. Simultaneously, there is a clear emphasis on levels 3–5, which involve more complex tasks and therefore require higher-order cognitive processes. With regard to the dimensions of graph competence, the focus is on tasks that address the domain-specific, content-related dimension, requiring the linking of chemical content knowledge with the form of graphical representation. This raises the question of whether upper secondary education students have developed the multilevel graph competence required to integrate both the formal and the content-related dimensions reflected in the tasks, particularly given that lower secondary education textbooks largely emphasize less demanding, domain-general tasks at levels 1–2. If such competence is insufficient, students may be overwhelmed by the breadth and increasing complexity of tasks in upper secondary education textbooks, potentially leading to cognitive overload (Sweller, 2005) or what Rau (2017) refers to as a representational dilemma. Accordingly, targeted support is needed to ensure that the necessary foundation, active engagement with multilevel graph-related tasks, is developed not only in upper secondary education textbooks but already in lower secondary education textbooks. This is especially important because, without such deep engagement, learners are likely to analyze graphs only superficially and will not fully understand the underlying subject matter (Jahnke, 2020).

Implications

Based on the findings of the study, implications for teaching can be derived. In general, it is important that students are systematically supported and encouraged in developing multilevel graph competence throughout their entire school career – across grade levels, subject matter that is represented in graphs, graph types, and regardless of the type of school they attend. This development can be fostered through the deliberate use of graph-related tasks that reflect the graph competence model in its entirety, including both information extraction and graph construction tasks. Moreover, all levels of the “information extraction” component need to be addressed to ensure that, over time, a sustainable and differentiated multilevel graph competence can emerge.

In order to provide students with adequate support when working on graph-related tasks and to foster their graph competence, it is generally essential that (prospective) teachers recognize the need to explicitly promote graph competence in chemistry lessons rather than relying solely on textbooks. Teachers should explain graphs in a language-sensitive manner, drawing on established quality criteria for instructional explanations in chemistry education (Fichtner & Groß, 2025b). The deliberate and targeted explanation of graphs in classroom practice is particularly important in light of our analysis, which showed that graph captions are

predominantly descriptive and often brief and therefore provide little support for students' comprehension (consistent with prior research, e.g., Bowen & Roth, 2002). Another implication for promoting graph competence directly through textbooks concerns the design, implementation, and use of strategy pages that explicitly outline steps for constructing, describing, explaining, and critically evaluating graphs. These pages provide students with a clear framework for approaching graph-related tasks and help them become aware of the domain-specific features of chemical graphs.

Moreover, appropriate scaffolds should be implemented and adaptively tailored to the specific difficulties that students experience when engaging with graphs. As a prerequisite, it is necessary to first identify the particular challenges that learners encounter when working with chemistry-specific graphs. The second study of the research project addresses this need by examining the difficulties learners face with different types of chemistry-specific graphs using tasks aligned with the levels of the graph competence model. Building on these findings, interventions will be designed that adaptively target the identified challenges and thereby support learners in developing graph competence. In this way, the research project contributes to contemporary chemistry education by fostering students' graph competence in ways that are valuable not only from an educational perspective but also for their everyday lives, particularly for navigating an increasingly data-driven world.

List Of Analyzed Textbooks

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What Comes To Mind When You Think Of Mechanical Engineering?

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*In recent years, there has been a notable decline in the number of first-year students pursuing STEM subjects, particularly in engineering. Consequently, measures have been implemented to promote STEM study programs. These measures focus on investigating the expectations associated with engineering degree programs and the perceptions of prospective students. As part of a study (n=339), the Inspir**ING**® project at Karlsruhe University of Applied Sciences gathered data on how pupils from 8th grade onwards perceived mechanical engineering. The data was collected in 2024 and 2025 and was analyzed using descriptive statistics as well as qualitative content and cluster analysis. While the pupils demonstrated some realistic associations with the subject, the results indicate that pupils currently lack the capacity to comprehend the course in its total breadth of content. This paper outlines survey results and provides an outlook for the future research project.*

Keywords: STEM, mechanical engineering, students' perceptions

Introduction

Recent years have marked a decline in the number of first-year students enrolled in STEM (Science, Technology, Engineering and Mathematics) subjects, particularly those pursuing engineering and technology courses, in Germany (Anger et al., 2024). This decline is of critical concern, particularly in light of the growing shortage of skilled workers. The present shortage is estimated to be approximately 140,000 academically qualified STEM specialists (Plünnecke, 2023). A sustained decline in student numbers is likely to adversely impact Germany's capacity for innovation in the long term and diminish its competitiveness in international comparison (Shambaugh et al., 2017; BDI et al., 2024). A marked downward trend has been observed in the field of mechanical engineering and engineering since 2011, with a decrease in first-year students of approximately 50% (Statistisches Bundesamt, 2025). In response to this decline, a significant number of STEM funding projects are being implemented by federal states, schools, universities and companies.

Notes

In order to differentiate between students (from 8th grade onwards) and students of engineering subjects at the university, the former are referred to as *pupils*, whereas the latter are described as *students*.

The German word "Maschinenbau" (Mechanical Engineering) is composed of the words "Maschine" (literally meaning: "machine") and "Bau" (literally meaning: "construction").

Background

The Inspir**ING**® project, an elective subject for engineering students, aims to raise pupils' awareness of technology and educate them about technical subjects. The task assigned to students is the design of a teaching unit on a technical experiment of their choosing, which they subsequently implement with pupils from grade 8 onwards. A questionnaire was developed for the purpose of investigating pupils' associations and perceptions of the degree courses in mechanical engineering, mechatronics, computer science and electrical information technology.

The questionnaire is of particular interest as perceptions and ideas are among the sociological factors that influence the decision to choose a field of study (Eccles & Wigfield, 2002). Furthermore, it is imperative to emphasize the pivotal role of attaining a comprehensive understanding of the practical domains associated with a specific degree program, and the cultivation of a realistic perception of the curriculum (Ziegler et al., 2013).

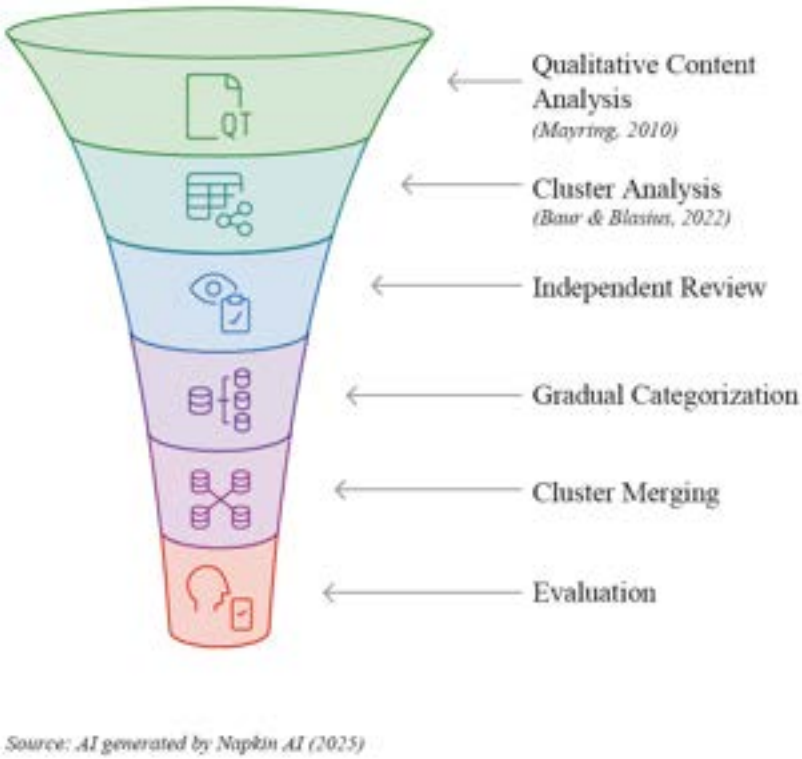
The objective of the survey is to obtain an overview of the associations of pupils with the subject of "mechanical engineering" and to compare them with the real profile of the course. By comparing these perceptions with the actual profile of the course, recommendations for action and potential solutions to improve the image of the Mechanical Engineering program can be formulated. These recommendations will subsequently be implemented into the Inspir**ING**® project and further use of the questionnaire.

Methodology

As part of the questionnaire employed in this study, respondents were invited to offer their opinion on mechanical engineering as a subject. This request was made in 2024 and 2025 to pupils in grades 8 and above (n = 339).

As shown in Figure 1 the data analysis was conducted using inductive qualitative content analysis according to Philipp Mayring (2010). This was followed by the implementation of a subsequent cluster analysis (Baur & Blasius, 2022), which was employed to identify clusters within the data.

Figure 1. Overview of the methodological approach



Source: AI generated by Napkin AI (2025)

Initially, the qualitative content analysis was employed to detect meaning structures in the data (Reinders et al., 2022). Qualitative content analysis embeds the material in the contexts of the entire communication, in this case the project and the questionnaire. For the systematic contextualization of the material, it is necessary to define (1) coding units as the smallest possible material component of the text; n the material; (2) context units as the largest possible text component of a category; and (3) analysis units to determine the order of the evaluations. Based on these predefined rules, the material was examined in light of the pupils' opinions regarding mechanical engineering. Following qualitative content analysis, data can either be summarized, explained by reference to additional information and structured by filtering the material according to pre-defined criteria (Mayring, 2015).

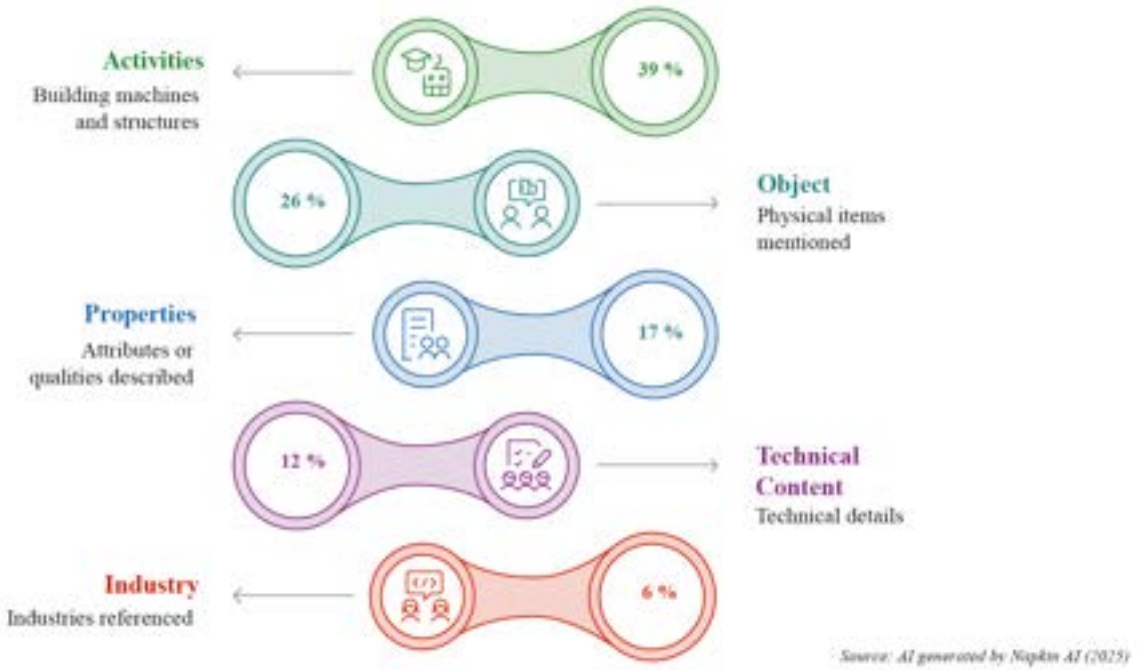
In this study, the data was systematically structured with regard to the importance and frequency of occurrence of pupils' opinions on mechanical engineering (Schneijderberg et al., 2022). To ensure the validity as well as the intercoder reliability of the analysis, the data was analyzed independently by two researchers.

In the next step, the pupils' responses were subjected to a process of gradual categorization. Consequently, they were divided into clusters based on their respective similarities. Within each cluster, the respective answers were evaluated regarding their realistic perception of the mechanical engineering degree program. The official study subject description "Mechanical Engineering" of the Federal Employment Agency Germany (Bundesagentur für Arbeit, 2025) was used as a basis for this. The pupils' answers (n = 468) were then evaluated using a three-point scale (1 - very applicable, 2 - applicable, 3 - less applicable). For instance: 3 - build; 2 - build machines, 1 - develop and build machines. These clusters were then successively merged with other similar clusters (Baur & Blasius, 2022). The initial results of this study are presented in the next section, followed by a descriptive illustration.

Findings

Through qualitative content analysis, the following central categories were identified (see Figure 2): *Objects, Activities, Industry, Properties,* and *Technical Content*. The pupils' perceptions were assigned to these categories without evaluative interpretation or anchoring to real-world or practical applications, ensuring an objective and content-faithful representation of the thematic domains expressed.

Figure 2. Categories identified after the qualitative content analysis



Preliminary results of the content analysis indicate that the largest proportion of pupils' perceptions (39%) falls within the category *Activities*. This finding suggests that pupils primarily associate the field of mechanical engineering with practical actions, processes, or hands-on tasks.

The second most prevalent category, O*bject*, accounted for 26% of associations. This category encompasses concrete artifacts, devices, or technical systems such as machines, tools, vehicles, or electronic equipment, thereby highlighting pupils' engagement with tangible technological artifacts that play a role in engineering contexts.

The category P*roperties* was identified in 17% of perceptions and encompasses descriptive attributes linked to the study of mechanical engineering. These include both positive characteristics (e.g., interesting, exciting, important) and negative perceptions (e.g., demanding, boring, a male-dominated profession), reflecting a range of affective and social associations.

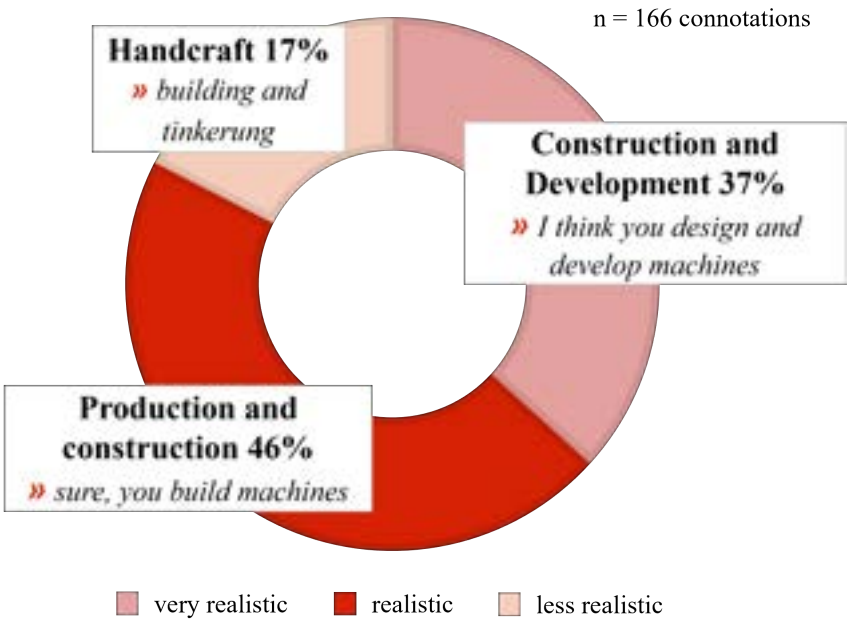
The category *Technical Content* received 12% of the responses, placing it significantly lower than the previous categories. It includes references to particular technical knowledge or disciplinary terminology such as mechanics, electricity, energy conversion, or materials science. While these responses indicate a higher level of subject-specific understanding, they remain relatively infrequent.

Industry is the category with the lowest frequency, accounting for only 6% of associations. Responses in this category are typically associated with companies located near pupils' homes.

Overall, the distribution of responses suggests that pupils predominantly conceptualize technical topics through actions and practical activities. The relatively infrequent responses in the *Technical Content* and *Industry* categories indicate that pupils' understanding of mechanical engineering remains largely superficial, with limited awareness of more profound technical knowledge or real-world industrial contexts.

In order to gain deeper insights into pupils' perceptions of mechanical engineering, a closer examination of the category *Activities* (39%, n = 166) reveals a more detailed breakdown in Figure 3. The chart categorizes pupils' responses into three primary domains: *Production and Construction* (46%), *Construction and Development* (37%), and *Handcraft* (17%). These categories offer valuable perspectives on how pupils conceptualize the field of mechanical engineering.

Figure 3. Distribution of perceptions within the category Activities with clustering into very realistic, realistic and less realistic



Note: Figure created by the author based on original data.

The largest segment of the chart reveals that almost half of the pupils associate mechanical engineering primarily with *Production and Construction*. This finding corroborates earlier observations that pupils frequently link the discipline to practical activities and tangible objects. The statement "sure, you build machines" exemplifies this perspective, thereby underscoring the hands-on, constructive nature of mechanical engineering. This association highlights the pivotal role of practical experiences, experiential learning and the tangible construction of machines and structures in shaping pupils' understanding of the discipline. As these associations are not incorrect but rather superficial, consisting primarily of the course name in German (see chapter **Note** for details), they are categorized in the cluster as *realistic* and not *very realistic*.

The second largest segment C*onstruction and Development* accounts for 37% of the perceptions. Pupils in this category perceive mechanical engineering as a process of designing and developing machines. The representative quote "I think you design and develop machines" reflects a more advanced understanding compared to mere production. This standpoint acknowledges the creative and innovative aspects of mechanical engineering, emphasizing the roles of planning, problem-solving, and technical expertise. These responses are categorized into the cluster *very realistic*, as they not only include object/activity descriptions but also describe processes in mechanical engineering. Nevertheless, it continues to prioritize the tangible outcomes of engineering endeavours rather than the underlying scientific principles or broader industrial context.

The smallest segment *Handcraft* represents 17% of the responses. Pupils in this category associate mechanical engineering with activities like building and tinkering. This perspective emphasizes the manual and craft-based aspects of the field, suggesting that pupils view mechanical engineering as a form of skilled labor involving hands-on work. While this association is valid, it overlooks the complex technical knowledge and theoretical foundations required in modern engineering practices. For this reason, it is placed in the last cluster *less realistic*.

The qualitative content analysis provided an understanding of how pupils perceive mechanical engineering. While practical activities and tangible objects dominate their understanding, there is a need to expand their knowledge base to include technical content and industrial contexts. Closing this gap through targeted educational strategies will be crucial to engage a new generation in studying mechanical engineering and to train versatile and informed engineers.

Outlook

The prevalence of practical and tangible associations in pupils' perceptions of mechanical engineering yields significant implications for STEM education. While experiential learning is essential for fostering interest and engagement, there is a need to broaden pupils' understanding by integrating deeper technical knowledge and real-world industrial applications.

The findings of this study may serve to encourage teachers to expose pupils to typical STEM questions, such as problem-solving tasks, from an early stage. This can raise pupils’ awareness of STEM disciplines and job profiles. In particular, prospects of those pursuing a career in mechanical engineering or recent graduates can be communicated by means of a hands-on approach. Experiments, laboratories, and projects can facilitate pupils in acquiring a more profound understanding of engineering sciences, thereby enabling them to develop a more precise conception of this discipline.

The results of the association questions concerning the degree programs, in particular mechanical engineering, demonstrate the importance and necessity of educating pupils in order to break down stereotypes, incomplete or even misconceptions and create awareness. Inspir**ING**® offers a good platform for this, where students not only inspire enthusiasm for technology, but also report on their personal experiences in the respective engineering degree programs as role models. The “Inspir**ING**® @ work” extension is also planned, in which students will present a technical career path or life plan that shows the path from school to the professional world. This initiative involves collaboration with the university's dual training program and corporate entities. In the future, Inspir**ING**® will also be offered not only for pupils from the 8th grade onwards, but also for kindergarten children in the format “Inspir**ING**® for Kids - Animals, Technology and University” in order to make technology visible and raise awareness of it at an early stage of development.

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Uses Of Fault And Fold Models In Geoscience Education: A Case Study In Upper Secondary Education

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[2]Université Virtuelle, Tunisia

Our research addresses the issue of the uses of models and modelling in geoscience education. We conduct a case study on the teaching-learning of tectonic deformations, i.e. folds and faults, in two upper secondary school classes in Tunisia. In these classes, teachers and students use models and modelling. Our aim is to understand how these models are used and how they can help students understand the deformation of the Earth's crust in the context of plate tectonics. To do this, we filmed the entirety of two practical work sessions on folds and faults in each of the two classes. Analysis of our data enables us to characterise the dynamics of knowledge construction through the use of concrete models and modelling during class sessions. This leads us to propose hypotheses of effectiveness concerning the use of models and modelling in geoscience education and to draw implications for the construction of classroom sessions)

Keywords: Models, modelling, geoscience education

General Description

Research in geoscience education covers a variety of contexts and theoretical frameworks (e.g. Francek, 2013; King, 2008; Le Hebel & Fontanieu, 2026; Oh, P. S., 2019; Orion, & Ault, 2007; Santini & al. 2018). It has shown that teaching and learning geological knowledge involves specific difficulties. For example, current geological structures are often perceived as permanent by students, preventing them from conceiving of change over time. Frodeman (1995) points out that the speed at which geological phenomena that are inaccessible to observation occur and unfold is imperceptible on a human scale, given the immensity of geological time. In this sense, Trend (2000) emphasises the difficulty to apprehend the timescales involved and orienting in the space. According to Raab & Frodeman (2002), students encounter difficulties in understanding long timescales and perceive the dynamism of geological processes. In addition to long time frame, the author indicates that even geologists cannot directly conceive of such spans but can understand them through "analogies with everyday experience". For example, geologists "manipulate blocks in their imagination to understand plate tectonics" (ibid., p.72). In relation to the difficulties associated with the size of geological objects, McLaughlin & Bailey (2022) points out that the question of representing space constitutes "a major and recurring obstacle". Therefore, problems of temporal and spatial scales lead educationalists to think of time and macro-space as epistemological obstacles (Bachelard, 2002)-insofar as these two concepts seem completely counterintuitive.

Furthermore, learning about geological phenomena is intrinsically a subject that often excludes direct experimentation as a means of teaching and learning, even for specialists. For these reasons, teachers use models as representations of geological phenomena or modelling activities to teach geoscience (e.g. Santini et al., 2019).

Based on our review of the literature, we note that no research work has been done on the issue of teaching and learning folds and faults in geoscience education, hence the need for the research presented here. In this research context, we addressed the following questions. How is modelling used in teaching and learning about folds and faults? How do models and modelling participate

effectively in the production of the knowledge at stake? How effective are the teaching practices studied in learning how to use models?

Theoretical Elements

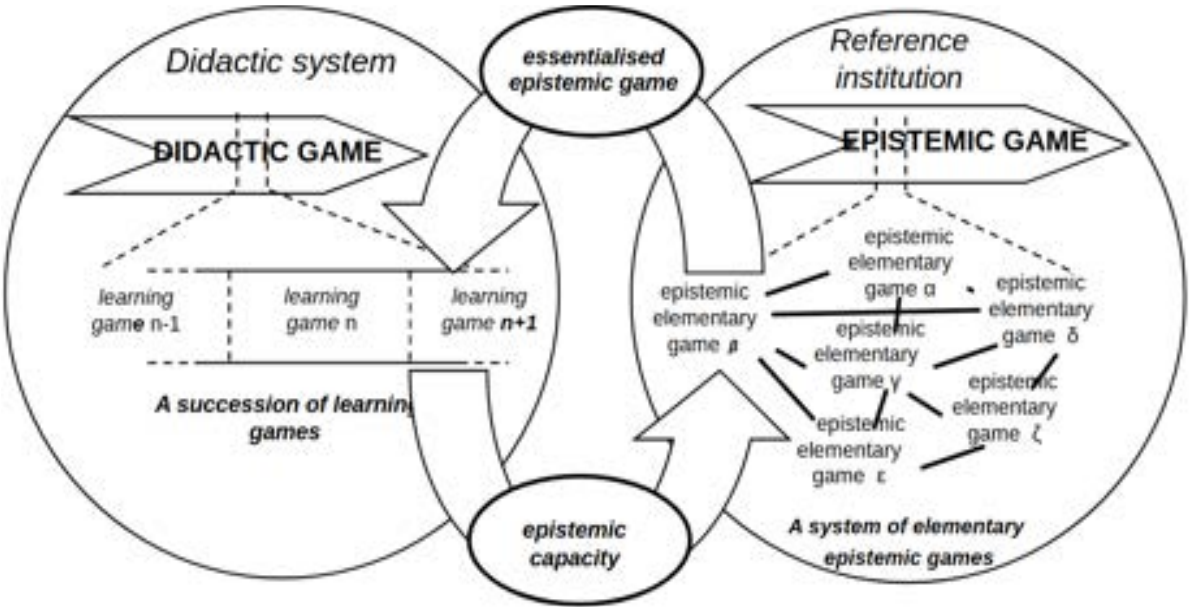
The Joint Action Theory In Didactics (JATD)

We situate our work within the Joint Action Theory in Didactics (JATD; Sensevy, 2011, 2019). JATD is part of an action-based approach to didactics. Didactics studies teaching and learning as the functioning of a system composed of three subsystems: the student, the teacher, and knowledge (Hudson & Meinert, 2011). Essentially, the research developed in JATD studies the teaching-learning process as a joint action between students and teachers, i.e. as a mutual adjustment in knowledge during classroom sessions (Tiberghien, 2016). Knowledge is considered to be indissolubly linked to the practices in which it has been forged, in other words the immanence of knowledge and practices (Bloor & Santini, 2023; Santini et al., 2018). Consequently, the study of geoscience education can be understood as the study of how educational practices allow students to approach geological practices.

Game Concepts In JATD

JATD proposes modelling didactic action in terms of games, with reference to Wittgenstein's language game (Wittgenstein 1997) and Bourdieu's social game, which makes human activity seem like a game (Bourdieu1990). In other words, the didactic action can be modelled as a succession of learning games (Sensevy et al., 2005). In this model, didactic action is described as a didactic game in which students and teachers act together in a didactic game through a succession of learning games. To clarify the generic grammar of didactic action, Santini (2021) uses a model of didactic action in a knowledge game model (Figure 1). Learning can then be understood as acquiring new *epistemic capacities*, i.e. capacities with the knowledge at stake, through participation in learning games.

Figure 1: The knowledge game model in JATD (based on Santini et al., 2018).



In JATD, epistemic games are a model of connoisseurs' practices for modelling phenomena of conceptual understanding in the Joint Action Theory in Didactics. In a nutshell, epistemic games model human practice with knowledge. This modelling is based on a theoretical postulate of the immanence of knowledge in human practices. Furthermore, we consider knowledge as a system

of capacities for action, with a certain efficiency in situations. In our knowledge game model, epistemic capacities represent the piece of knowledge in learning games. Under this description, teaching effectiveness is understood as the continuity (Dewey, 1938) between learning games (what the teacher makes students do in order to learn) and epistemic games (what those who know how to do something, the experts, do).

In this paper we focus on learning games. This concept is defined by the transition from one "scene" to another in a teaching-learning sequence, and thus the actualization of new knowledge at stake. These scenes are defined as being connected and self-contained and are generally delimited by an introduction and a conclusion (Sensevy et al., 2015). Learning games are using the concept of didactic contract and didactic milieu.

The Didactic Contract

The didactic contract (Brousseau & al. 2014) constitutes "the set of (specific) behaviours of the teacher that are expected of the student and the set of behaviours of the student that are expected of the teacher". From the perspective of JATD, the didactic contract constitutes a system of rules defining "how to play" and strategic rules for "how to win" in order to play the learning game.

The Didactic Milieu

A learning game is supported by a system of objects that resist the student's actions. This system can be described using the concept of didactic milieu (Sensevy, 2015). The concept of didactic milieu accounts for the set of resources, material and cognitive constraints present in the learning game. This means the milieu is the medium that supports the actions of students and their teachers.

Following Sensevy (2015), we note that didactic milieus and didactic contracts are inseparable, and that a change in the milieu requires a change in the contract.

Models And Modelling In Science Education

Previous researches about models and modelling in science and in science education are numerous. Models are intermediaries between theory and practice (Hacking, 1983). They link objects and events (empirical field) on the one hand, and theories and laws (theoretical field) on the other (Buty et al., 2004).

According to Sensevy et al. (2008), sciences produce explanatory models of the world, but not of the world as it is, but rather of the world as it is reconstructed. Santini et al. (2019) demonstrated that teaching practices can involve representational and/or heuristic uses of concrete models. They concluded that, depending on the uses to which students are exposed, they acquire different understandings of models and modelling in science.

However, Gilbert & Justi (2016) emphasise that models represent not only objects, events or processes in the real world, but also data. Thus, models are partly independent of both reality and theory, as Cartwright (1983) had already pointed out. Gilbert & Justi (2016, p. 22) cite Morrisson and Morgan (1999) who propose that models function autonomously, i.e. they serve as intermediaries between reality and theory. They also consider models to be tools for investigation in scientific practices, as vectors for learning about the world. Morgan (1999) also considers models to represent ideas and have predictive power, which characterises them as active tools in the construction of scientific knowledge.

Following these authors, we think that the problems posed by the use of models and modelling activities ultimately raise fundamental questions such as: what should be explained to students? How can we move from a local scale to a global scale? How can we move from a microscopic explanation to a macroscopic explanation of tectonic deformations?

Methodology

Our research is based on the making and analysis of films of classroom sessions (Tiberghien & Sensevy, 2012). Our research corpus consists of two classes at grade 11 in Tunisia, comprising 30 French-speaking students aged 17 to 18, taught by two teachers T1 and T2. We then filmed the "folds and faults" sessions from start to finish. To analyse them, we followed a methodology close to that described by Kelly (2016) for the study of epistemic cognition in action. Following him we thus proceed in three stages of analysis. After viewing both sessions several times, we transcribed the video recordings in full. The transcripts obtained are used to prepare a synopsis of the classroom sessions, providing a comprehensive overview and conduct an overall analysis of the sessions. We then structured the transcription of the two sessions observed in terms of learning games, which enabled us to carry out detailed analyses and, finally, to reconstruct the unfolding of the knowledge at stake in action.

The transcriptions of the videos were made using the Transana analysis software (Woods, 2025), which helps to understand the interactions between teachers and students, as well as the gestures and attitudes of interest in terms of the knowledge at stake (Badreddine & Buty, 2011). In what follows, we present the analysis and discussion of the results obtained from the transcription of the videos of the classroom sessions.

Results

Each of the two teachers began with the study of pictures of outcrops of folds and faults (Figure 2).

Figure 2. Photographs of various geological outcrops observed in nature.



They asked the students to observe, put forward explanatory hypotheses about the forces responsible for these tectonic deformations and formulate a scientific problem. The students mainly agreed that the strata that are initially deposited horizontally undergo tectonic deformation over geological time under the effect of natural forces.

To test this explanation, the two teachers used concrete models and activities to model folds and faults. It should be noted that both teachers follow the same official curriculum, which entails that their lesson plan is almost the same. We analyse the unfolding of each classroom sessions and model them as a succession of learning games. This method enabled us to construct synopses of the two sessions based on the transcripts and videos, which we present in the table 1 below.

Table 1. Synopsis of the two sessions observe.

Learning games in T1 and T2's sessions	Model used in T1's session	Model used in T2's session
1. Applying two opposing converging forces to a series of flexible plastic rulers	Plastic ruler Flashs Animations	Plastic Ruler
2. Describing the result obtained, put forward a hypothesis to explain the formation of folds and define a fold.		
3. Compiling the document from Activity 1 and determine the properties of the fold.	Video	
4. Observing the following digital simulations and identify the characteristics of each of the two straight folds	Flashs Animations	Photos
5. Applying two compressive forces of increasing intensity to the rigid plastic ruler.	Rigid plastic plate	Rigid plastic plate
6. Giving an interpretation and define a fault		
7. Applying two compressive or stretching forces of increasing intensity to the wooden model on the bench.	Diagram blocks Video sequence from a didactic model	Diagram blocks
8. Looking at the numerical simulations for compression and extension and identify the properties of each type of fault.	flashs Animations	Video
9. Completing the legend for activity games 5 to 8.		
10. Constructing a conceptual, explanatory and summary map of tectonic deformations.		

Table 1 presents T1's and T2's classroom sessions modelled as learning games. We have chosen to examine game 1 of the two class sessions as they share common objectives: understanding and explaining flexible tectonic deformations. We now present an overall analysis of the two sessions and an analysis of an extract from the first learning game in T1's and T2's class.

Analysis Of The First Learning Game In T1's Class

In our study, the teacher described the ruler as a geological layer, and the students described the curved ruler as a layer (Figure 3).

The overall analysis of the T1's session after viewing the filmed session several times, and the full transcript of the video recording, reveals that the knowledge at stake progress rapidly from the pictures to the explanation of the formation of folds in nature. We also note that the division of responsibilities regarding the knowledge at stake between the teacher and the students was generally balanced. The teacher defined the learning game, leaving it up to the students to name the deformation modelled. The activities during the T1's session were generally balanced the same way, with the teacher intervening and the t students following and responding to the interventions of teacher T1. In fact, we note that the naming of the deformation modelled as a fold is not done by the student alone, nor the teacher alone, but a co-construction in joint action, based on the operation of the model. The full transcript of the film recording of the P1 session also shows that the students participated in the development of the didactics milieu. The extract

below illustrates how teacher P1 regulated the didactic milieu. When a student introduced the term "wave-like layers," "folding" or "deformation," the teacher T1 repeated the term and lead the students to explain the formation of folds in the Earth's crust and the conditions for applying the principle of superposition.

Figure 3. Tectonic deformation modelling.



The Determinants Of T1 Teaching Practice

Below we present an analysis of an extract from learning game 1 in the T1's class.

Box 1. Extract from the first learning game in T1's class.

T: what has happened to this layer? Does it remain horizontal?

S: The layer has undulated

S: a downward or upward curvature.

S: it undergoes a deformation

S: the layer is folded

T: very well, the layer is folded under the effect of what?

S: under the effect of lateral compression forces

T: asks the student to add another plastic ruler and to repeat the experiment)

T: What do you find? Can we now apply the principle of superposition?

Analysis of this extract shows a representational use of the model: the model replaced reality, and the students worked on the model as if it were reality. It seems that the model has lost its status as a learning tool and a tool for questioning reality and became a teaching object and objective in itself. We also note a heuristic use of the model: the model was used to reason about the principle of superposition. The model was no longer used simply to represent reality, but to test the validity of the principle of superposition in the case of a fold. The interesting thing about this extract is that it combines a representational use and a heuristic use of the same model.

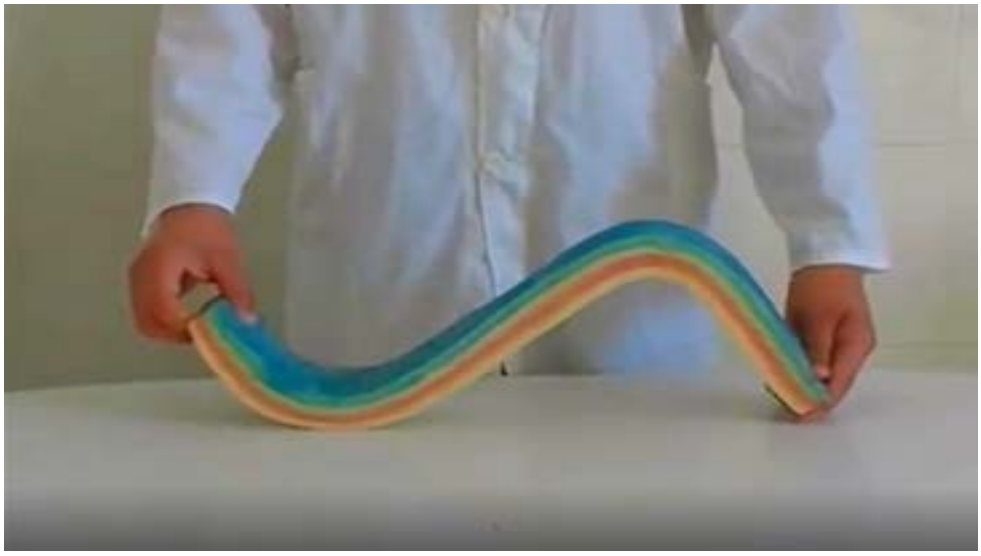
Analysis of this extract also shows that the students did not spontaneously use the term "fold", even though it was used to describe a photo from the pre-test. Among the previous answers, the teacher echoed "folding" by using "folded". In so doing, he pointed out that "fold" was the expected scientific term. This term can now refer to an experience the students had with the model and was therefore more likely to make sense. However, we note the echo he had given, in a previous turn, to "folding". This gave the students a clue as to how to respond.

In short, Teacher T1 relied on an active teaching strategy rich in interactions (manipulation, question/answer between the two instances of didactic action) guided by his own practical experience. He worked collaboratively with students in an interactive dynamic. We would also point out that teacher T1 did not integrate the use of the model into a global tectonic framework and limits himself to a local explanation.

Analysis Of The First Learning Game In T2's Class

In the first learning game, the teacher described the layers of modelling clay as geological layers, and the students described the curved layers of modelling clay as layers too (Figure 4).

Figure 4. Tectonic deformation modelling.



An overall analysis of the P2 session shows that the advancement of knowledge at stake is mainly due to the teacher. However, T2 slowed down when students encountered learning difficulties. The division of responsibilities about the knowledge at stake was relatively balanced between T2 and the students. T2 seeked to involve the students in the elaboration of the knowledge. He regularly encouraged the students with the words "very good". A global analysis of the session also reveals that teacher T2 was primarily responsible for the evolution of the didactics milieu. Indeed, we note here the main role played by T2 in the establishment and development of the didactic milieu, as he introduced more objects into the environment than the students did.

Using Box 2, we analyse the models used by T2 in the same way as the T1 class above. Analysis of the extract of the first learning game reveals that T2 used interdisciplinarity. Indeed, he reinforced the link between physics and geoscience by citing experiments on wave propagation in physics to help students formulate answers about the undulations of geological layers in order to define a flexible deformation. In addition, he was more comfortable managing interactions in the classroom. We note that T2 mainly used models as representations of reality, and that the heuristic uses of models are limited and brief. Furthermore, T2's attention was focused on student interactions. Indeed, he sought to comply with official curricula while diversifying models. We also note that teacher P2 has not integrated the use of models into a global tectonic framework and limited their uses for local explanations like T1 did.

We analyse all the models used in the same way as the extract above. We find that both teachers predominantly used models as representations of reality. The heuristic uses of models were limited and brief. The models were not placed in a global tectonic framework.

Box 2. Extract from the first learning game in T2's class.

T2: asks a student to apply increasing amounts of compressive force (convergent) to layers of modelling clay of different colours.

S: guided by the teacher, the student carries out the demonstration experiment for their classmates.

[Deformation of the layers initially placed horizontally].

T: what did you observe?

S: Under the effect of the compressive forces, the layers do not remain horizontal.

T: Yes, excellent answer.

T: What did they undergo?

S: The layers underwent undulation, a curvature directed upwards and downwards.

T: Very good, so by simulating this experiment, what is the nature of the rocks in the slide? S: Plastic. S: Elastic. S: Flexible.

T: When the rocks are flexible, what do we get?

Discussion And Conclusions

The analysis of didactic actions shows that teaching practice can involve representational uses of concrete models, where study of the model replaces study of the phenomenon itself.

We think that allowing students to use models more heuristically should help them to better understand geological phenomena and the usefulness of models. For example, in the extract analysed, students could have been asked to argue why the principle of superposition cannot be applied here. In this way, students could have learnt that a model can be used to test a theoretical principle.

We note that teachers followed the textbook, but not everything was determined by the textbook in the construction of the sequence. In fact, the teachers choosed the same object as the rule and varies a flexible or rigid property to encourage comparison between the two models.

In conclusion, it seems that the models used were not integrated into a global tectonic framework, which made impossible to know where the forces exerted come from. This seems to us to be a necessary part of geoscience education at the upper secondary level. It would thus be possible to link the various models used in a global tectonic framework to explain the forces they bring into play. In the excerpt analysed, this would lead to make explicit the pressure of the hands on each edge of the ruler within the framework of a convergence regime. In addition, despite the same official programme, analysis of the action shows that similar models were not exactly used in the same way in the two classes. We think that this difference in the uses of the models may determine part of the effectiveness of their teaching.

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Part 19 / Strand 19

Teaching And Learning Science At The University Level

Co-editors: *Hendra Agustian & May Lee*

Part 19 / Strand 19 Teaching And Learning Science At The University Level

Science teaching and learning theories, methods, pedagogies and empirical studies at the university level. Includes discussion, interpretation, implication and reflection of praxis, as well as innovative proposals and policies of teaching and learning science at university.

Sub-themes:

1) Undergraduate Teaching
2) Undergraduate Learning
3) Graduate Teaching
4) Graduate Learning

Contents

Strand 19: Teaching And Learning Science At The University Level 1733

Is It Really Science *Vs.* The Humanities? A Cross-Discipline Study Mapping University Students' Knowledge, Attitudes, And Behaviour Toward Ocean Sciences Issues 1734

What Are Students' Learning Goal Orientations In The Analytical Chemistry Laboratory? . 1742

Supporting First-Semester Chemistry Students: Development And Evaluation Of A Two-Phase Digital Learning Unit In Redox Chemistry 1748

Representational Competence In The Context Of Electric Fields: An Eye-Tracking Study .. 1753

Improving Problem-Solving Skills Using Entrepreneurial STEM Intervention 1759

Strand 19: Teaching And Learning Science At The University Level

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Introduction

Strand 19 of ESERA focuses on teaching and learning in higher science education, encompassing research and practice across various curricular, pedagogical, and sociocultural aspects of science beyond K-12. Given the academic structure of higher education, the themes covered in this strand are typically discipline-based, such as Chemistry, Physics, and Pharmaceutical Science, but also inter- and transdisciplinary, such as STEMM (science, technology, engineering, mathematics, and medicine) and involving HASS (humanities, arts, and social sciences).

Overview

The ESERA 2025 conference theme, "Transitions in Science Education: Sustainability and Digital Advances," invites us to reflect on how profound ecological and technological transformations are actively reshaping higher education. In Strand 19, the contributions centred on how higher education navigates these shifting landscapes as they prepare the next generation of scientists, educators, and citizens to combat environmental crises, and adapt to the rapidly advancing digital technologies that shape modern learning.

The research papers presented in this strand show how transitions between academic, professional, and/or civic realms can be navigated from five perspectives. These perspectives include examining the cross-disciplinary boundaries of environmental (ocean) literacy, evaluating the entrepreneurial framing of chemistry topics for teacher education, and assessing the evidence-based digital tools used to scaffold students through high-stakes academic transitions, characterising students' learning-goal orientations and motivation in the analytical chemistry laboratory, and tracing how students perceive and coordinate multiple visual representations of electric fields. Collectively, they show how science teaching and learning at the university level can embed rigorous disciplinary knowledge with real-world technological, societal, and ecological relevance to support the transitions students face in higher education.

ESERA 2025 Copenhagen

Is It Really Science *Vs.* The Humanities? A Cross-Discipline Study Mapping University Students' Knowledge, Attitudes, And Behaviour Toward Ocean Sciences Issues

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The ocean environment is an integral part of the Earth's interconnected global ecosystem. Despite its immense scale and capacity to buffer changes, the ocean faces severe environmental challenges. Under the prism of Sustainable Development Goal 14 of the Agenda 2030 focusing on conserving and sustainably using the oceans, seas and the marine resources, and the United Nations Decade of Ocean Science for Sustainable Development (2021-2030), the present study attempts to highlight the persisting deficit in the Ocean Literacy field by focusing on two major categories of university students: those enrolled in Science and Humanities disciplines. Based on current research, the study argues that both fields can support ocean protection and sustainable management of its resources as content science knowledge is only one dimension that leads to pro-environmental attitudes and behaviour. In this regard, a structured questionnaire was administered to 495 university students from eight Science and Humanities Departments in Greece and Italy. The results showed low to moderate content knowledge, favouring science students, as expected, but common misconceptions were present. However, all students showed satisfactory pro-environmental attitudes and behaviour. These findings suggest that not only natural science experts, but anyone interested in the ocean can be receptive to scientific concepts, even if unfamiliar, such as those in ocean sciences.

Keywords: Ocean Literacy, Science students, Humanities students

Introduction

Marine and Aquatic Education has its roots in the environmental movement of the 1960s and 1970s, while its necessity had already been underlined and studied in parallel with the progress in Environmental Education, following a similar path in the 1970s and 1980s (Mogias et al., 2022). However, in the mid-1990s, a lack of ocean-related subjects was realised in the US formal science education standards, and the need for a more comprehensive framework to encourage the inclusion of ocean sciences emerged (Payne et al., 2022).

The concept of Ocean Literacy (OL) was defined in the early 2000s as an "*understanding of the ocean's influence on humans and our influence on the ocean*" (Cava, 2005). A series of workshops brought together governmental and non-governmental organisations, educators, scientists, and policymakers to define important concepts about the ocean and its resources. This effort led to a comprehensive framework with a set of seven principles and, initially, forty-four

concepts about ocean issues. An updated version added a forty-fifth concept almost a decade later (NOAA, 2013). The framework also included a pedagogical guide for teachers to use ocean content in teaching science from kindergarten to high school. It gave recommendations about when and how to insert ocean concepts into the K-12 science curriculum. These guidelines are now widely accepted and have inspired many initiatives worldwide. Although OL started as a knowledge concept, it has evolved into a multi-perspective approach, aiming at a society that understands, values, and cares for the ocean (Glithero et al., 2024). Current research in OL suggests several dimensions: awareness, knowledge, attitude, communication, behaviour, activism, emotional connections, access and experience, adaptive capacity, trust and transparency. These should also be considered when designing OL initiatives and interventions (McKinley et al., 2023).

To this aim, the 2030 Agenda for Sustainable Development, adopted by all United Nations Member States in 2015, included 17 Sustainable Development Goals (SDGs), among which a stand-alone goal focusing on the ocean (i.e., SDG 14) has been a major achievement for the global ocean community. In parallel, the United Nations declared the Decade of Ocean Science for Sustainable Development (2021-2030), seeking to contribute to the achievement of SDG14 and to extend its scope to fill the gap from "*the ocean we have*" to "*the ocean we want*". The concept of OL is central to operationalising Challenge 10, which aims to "*ensure that the multiple values and services of the ocean for human well-being, culture, and sustainable development are widely understood, and identify and overcome barriers to behaviour change required for a step change in humanity's relationship with the ocean*" (UNESCO-IOC, 2021).

Towards this direction, assessment and enhancement of OL issues among university students, the youngest active citizens who should use ocean knowledge and skills of ocean issues to communicate about the ocean in a meaningful way and make informed and responsible decisions, is required. This study aims to assess the levels of specific OL dimensions, such as knowledge, attitudes, and behaviour of university students coming from different disciplines of Science and Humanities Departments, and to reveal the potential needs and gaps while giving proper recommendations for mainstreaming ocean science issues into formal higher education.

Materials And Methods

A cross-discipline study was conducted on students attending eight Departments from four Universities in two European countries, Greece and Italy (Figure 1). The Departments were grouped into two general discipline fields, Science and Humanities; the total sample comprised 495 students. Table 1 shows the distribution of students by country, discipline, and gender. Two main hypotheses were tested regarding ocean sciences issues: (a) students enrolled in Science disciplines prevail, regarding ocean content knowledge, over students enrolled in Humanities, and (b) content knowledge strongly affects pro-environmental attitudes and behaviour.

A structured questionnaire to investigate knowledge, attitudes, and behaviour toward ocean sciences issues was developed according to previous research (e.g., Mogias et al., 2015; 2019) following the OL Framework (NOAA, 2013) and administered to students in the spring semester of 2024. The research tool contained demographics, a knowledge scale with 32 close-ended questions, and an attitude and behaviour scale with 10 statements each, following a 5-point Likert scale, revealing the degree of participants' agreement. Descriptive (relative frequencies, mean values, and standard deviations) and inferential statistics (t-tests and One-Way ANOVAs) were implemented using SPSS v.29; a probability value of 0.05 or less was predetermined as the significance level.

Figure 1. Location of the University Departments per country.



Results

Of the 495 students comprising the total sample of the study (almost two-thirds females), 48.3% emerged from Greek and 51.7% from Italian University Departments; accordingly, 58.6% had enrolled in Science while the rest in Humanities disciplines. Table 1 reveals in detail the sample distribution of the study. All students seem to choose the Internet as their primary source of information regarding environmental issues (4.08±0.987 and 3.83±1.027 for Science and Humanities students, respectively), while the former group also seem to prioritise the university faculty (3.61±1.112), academic textbooks (2.77±1.219), and scientific papers (2.69±1.320); on the contrary, TV appears to be the Humanities students' next highest preference (2.85±1.152), followed by friends and family (2.64±1.059) (Figure 2).

Table 1. Sample distribution of the study.

Country	Department	Discipline	Number of students (N)	Gender (%)	
				males	females
Greece	Marine Science	Science	85	49.4	50.6
	Environment	Science	56	42.9	57.1
	Primary Education	Humanities	55	16.4	83.6
	Education Sciences in Early Childhood	Humanities	43	2.3	97.7
Italy	Natural Sciences	Science	52	52.9	47.1
	Geological Sciences	Science	97	50.5	49.5
	History & Culture	Humanities	24	35.4	64.6
	Classical Philology & Italian Studies	Humanities	83	21.1	78.9

Students coming from both fields were found to possess rather low to moderate levels of ocean sciences content knowledge (mean score 16.60±5.278 for Science and 11.57±4.389 for Humanities students) but, at the same time, very positive attitudes and behaviour towards relevant issues (Figure 3). A statistically significant difference between the two discipline groups was recorded only for the content knowledge dimension ($p \leq 0.001$) (Figure 3a), while this was not the case for the other two dimensions; on the contrary, a statistically significant difference is depicted between attitudes and behaviour for each group ($p \leq 0.05$ and $p \leq 0.001$, respectively), with the former scale clearly prevailing (Figure 3b). Figures 4 and 5 reveal that despite the existing differences between the two main categories of students, they present comparable depictions in terms of the questionnaire items; more specifically, focusing on the content knowledge items, we

detect that almost the same questions were hard and, respectively, the same ones were easy to correctly answer (Figure 4).

Figure 2. Mean values of the preferred information sources. by Science and Humanities students

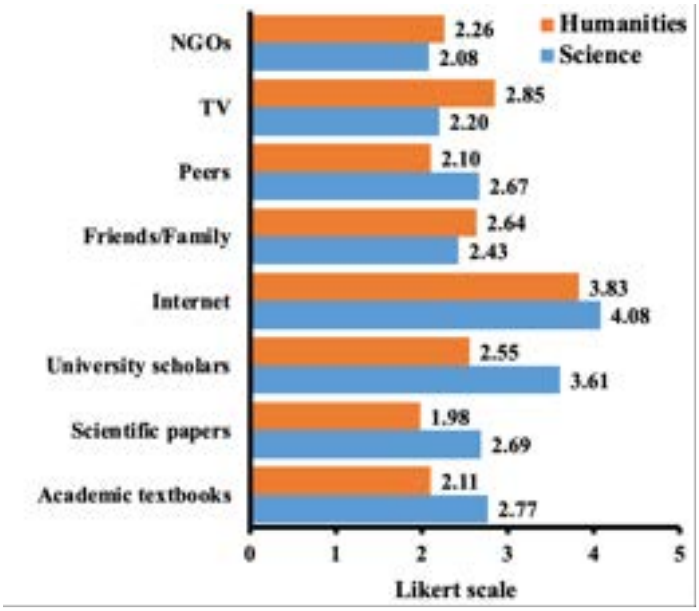
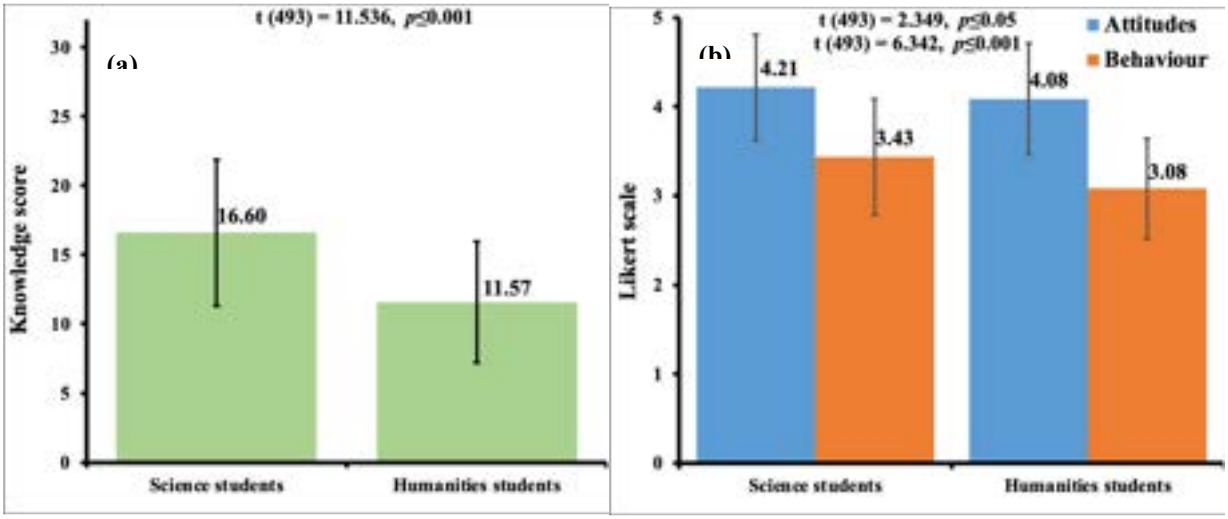


Figure 3. Mean knowledge (a), and attitudes and behaviour (b) values of Science and Humanities students



The common most difficult to answer items were questions 1, 16, 26, and 30, referring to the interconnection of all sea basins (mean value 3.4 and 4.9% for Science and Humanities students, respectively), the ocean's role in the global carbon cycle (22.1 and 19.0%), the vital role of estuaries (16.9 and 9.3%), and the basic sources of oil spills (8.0 and 7.8%); the common easiest questions to answer were 7, 8, and 29, referring to the transportation of several materials through rivers and watersheds to the ocean (mean value 84.1 and 82.9% for Science and Humanities students, respectively), the evidenced existence of seas and lakes million years ago in present-day terrestrial surfaces (87.9 and 81.0%), and the modern society's influence on the ocean (81.7 and 83.9%) (Figure 4). In terms of the other two scales, namely attitudes and behaviours, our findings portray amazing similarities between the two groups of students when depicting their level of agreement across all statements; more specifically, the attitude statements fluctuated between 3.72 (±1.054) and 4.48 (±0.768) (Figure 5a, Table 2), while the behaviour statements between 2.29 (±1.221) and 4.68 (±0.793) (Figure 5b, Table 3).

Figure 4. Fluctuation of correct answers provided by Science and Humanities students regarding the knowledge scale of the research tool.

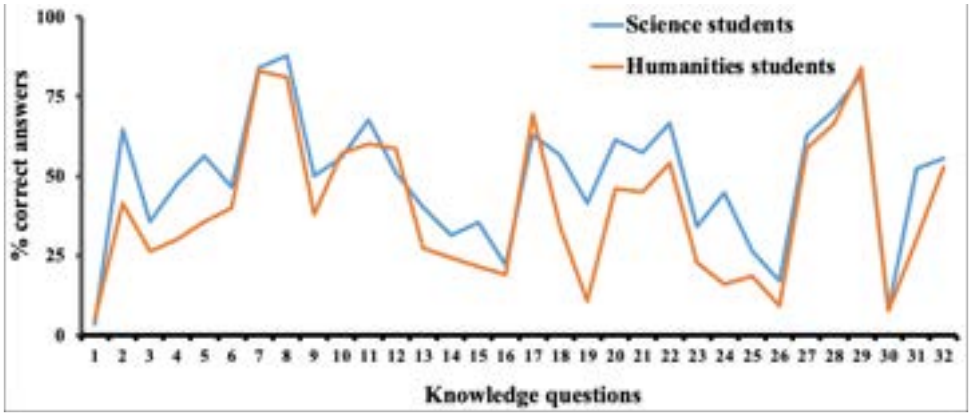
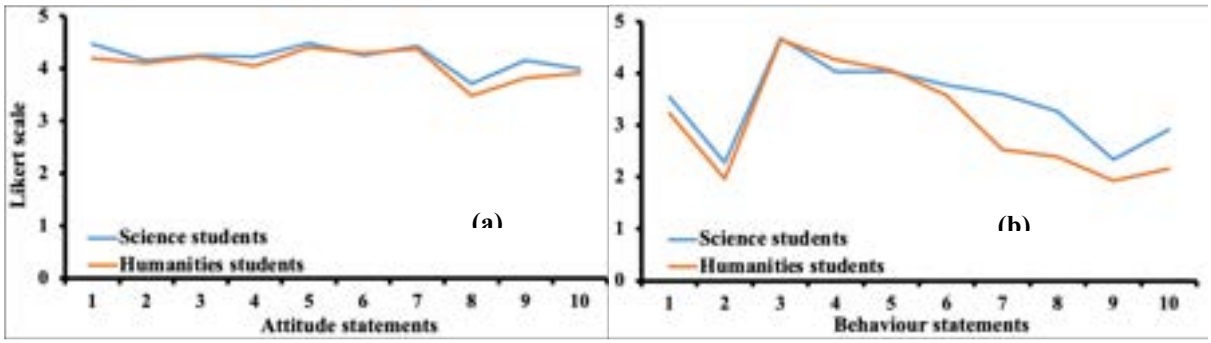


Figure 5. Fluctuation of values provided by Science and Humanities students regarding the attitudes (a) and behaviour (b) scales of the research tool.



Discussion

The aim of this study was not to compare students based on their nationality, nor among the Science and, respectively, the Humanities Departments. Our main interest focused on assessing the potential existing gaps between students attending these two scientific fields, primarily in ocean content knowledge, and whether these gaps could, and to what extent, influence their pro-environmental attitudes and behaviour. The results revealed low to moderate knowledge of ocean sciences issues in favour of Science students as expected, sharing the same misconceptions, while they exhibited positive attitudes and behaviours. These findings are in line with the existing literature (e.g., Koulouri et al., 2022; Mogias et al., 2019; 2022) targeting several populations, such as primary and secondary school students, and pre-service teachers, among others.

Our findings confirmed our first hypothesis regarding ocean content knowledge levels, based on the nature of the students' disciplines, but rejected the second one regarding knowledge impact on other OL dimensions such as attitudes and behaviour, as Humanities students with a comparatively decreased content knowledge exhibited almost equal positive attitudes and behaviours to their Science peers. Results of this study indicate that the involvement of other dimensions, such as emotional connections, access and experience, adaptive capacity, trust, and transparency, could promote pro-environmental attitudes and behaviour as these were portrayed by the work of McKinley et al. (2023). Moreover, modern teaching and learning require multi-perspective approaches (e.g., scientific, historical, geographic, among many others) that promote interdisciplinary, inclusive, and intercultural competencies (e.g., Santoro et al. 2017). Furthermore, the inter- and multi-disciplinarity that connects freshwater, marine, education, and social scientists is an acknowledged way of communicating complex ocean issues (Mokos et al., 2022).

The White Paper for Challenge 10 of the UN Ocean Decade, referring to "*Restoring Society's Relationship with the Ocean*", emphasises the major societal transformations needed to create a sustainable and equitable future (Glithero et al., 2024). Behaviour changes in personal, emotional, and cultural connections with the ocean are necessary beyond conventional scientific methods and proper science communication under the prism of Education for Sustainable Development (ESD), climate education, and global

citizenship.

Table 2. Mean values and standard deviations (sd) portraying the sample's level of agreement in the attitude scale.

	Attitude statements	Science students		Humanities students	
		mean	sd	mean	sd
1	I believe that human life is inextricably linked to the ocean	4.47	0.773	4.20	0.819
2	I feel frustrated with the overexploitation of marine resources at risk of depletion (e.g., fish)	4.16	1.017	4.11	0.956
3	I am concerned that human activities carried out on land (e.g., industries, agriculture) significantly affect the health of the marine environment	4.25	0.851	4.22	0.874
4	I feel frustrated when the leaders of several countries postpone the necessary measures to protect the ocean	4.23	1.104	4.05	1.167
5	I feel frustrated that sensitive marine ecosystems will be lost if humans do not change their behaviour towards the marine environment	4.48	0.768	4.40	0.718
6	I believe that humans are responsible for the extinction of many marine species	4.25	0.840	4.29	0.901
7	I believe that all of us, regardless of whether we live near the ocean or far from it, are responsible for protecting it	4.42	0.752	4.38	0.860
8	I feel personally responsible for protecting the ocean	3.72	1.054	3.48	1.162
9	I would like to get to know the marine environment better so that I can protect it and contribute to its future conservation	4.17	0.997	3.82	0.999
10	I would like to contribute to the protection of the marine environment, although I feel that I cannot do much on my own	3.99	0.988	3.91	0.974

In conclusion, attempting to provide an answer to the dilemma already presented in the title of the present study, we should all agree that current environmental issues require multi-perspective and innovative approaches. The concept of OL aims to connect ocean science and ESD through behavioural change initiatives and the adaptation of a systems approach. Continuing to invest almost exclusively during the past decades in experts' education proved not to be the best practice; what we need is to create a universal culture for the general public, which will eventually guide us to active citizenship. Only in this way will we be able to understand that the vitality of the ocean is inextricably connected to our survival, and thus collaborate towards its conservation, protection, and sustainable management of its resources.

Table 3. Mean values and standard deviations (sd) portraying the sample's level of agreement in the behaviour scale.

	Behaviour statements	Science students		Humanities students	
		mean	sd	mean	sd
1	With my lifestyle I try to reduce the impact I have on the environment in order to protect the ocean	3.54	0.931	3.22	1.084
2	I participate in organized social actions for the protection of the marine environment (e.g., beach cleaning)	2.29	1.221	1.97	1.026
3	I collect my trash when I'm on the beach	4.68	0.793	4.65	0.750
4	I avoid playing with marine organisms, even for a few minutes when I am on the beach	4.04	1.241	4.27	0.998
5	I recycle and reuse plastic, as it has a significant negative impact on the marine environment	4.03	1.027	4.07	1.050
6	I am opposed to the construction of houses and hotels on the beach, as it negatively affects the coastal and marine environment	3.78	1.224	3.57	1.153
7	I explore the diversity of marine life when I get the chance to do so	3.60	1.242	2.54	1.190
8	I encourage my family and friends to learn more about the marine environment and how to protect it	3.27	1.317	2.40	1.136
9	I know enough about the ocean and the problems it faces, but I still don't change my daily habits to protect it	2.34	1.025	1.93	0.910
10	I motivate my friends to learn more about how to protect the ocean	2.91	1.198	2.17	1.067

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What Are Students' Learning Goal Orientations In The Analytical Chemistry Laboratory?

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This study explored students' learning goal orientations in the analytical chemistry laboratory to gain insights on students' motivational patterns and how these vary by gender and cohort. Using the SELLMO-ST scales, the study assessed 273 students across five different cohorts. Learning goals emerged as the most prominent orientation, indicating high intrinsic motivation, while performance-approach goals exerted moderate influence. Performance-avoidance and work-avoidance scores were relatively low, suggesting that most students actively engaged with laboratory tasks. Gender differences revealed slightly higher performance-avoidance tendencies in female students, reflecting a stronger fear of failure. Overall, all student cohorts showed high learning goals which may arise from a shared enjoyment of the practical aspects of the laboratory course. Three distinct student profile groups were identified: 49% students with a strong focus on learning (profile 1), 32% students which combined learning with a performance-approach (profile 2), and 19% students with a high tendency to performance-avoidance and work-avoidance (profile 3). These findings highlight the importance of fostering intrinsic motivation and tailoring laboratory experiences to address diverse motivational patterns in chemistry laboratory education.

Keywords: Undergraduate Teaching, Laboratory, Motivation

Introduction

Research in chemical education has explored how students feel when learning chemistry and how this may be influencing how they perform. (Flaherty, 2020) One aspect is students' learning goals orientation, which play a crucial role in shaping their motivation, emotional engagement, and academic success. Learning goals are rooted in achievement goal theory (Urdan & Kaplan, 2020) which is closely linked to self-determination theory (Ryan & Deci, 2000). Both theories emphasize the interplay between intrinsic and extrinsic motivations in shaping students' engagement and success. It categorizes goals into mastery goals, which focus on developing competence and understanding, and performance goals, which emphasize demonstrating competence relative to others (Elliot & McGregor, 2001). These goal orientations are closely tied to emotional experiences, as students' motivations influence their perceptions of success and failure. Intrinsic motivation, linked to mastery goals, fosters adaptive behaviours like persistence and deep learning, alongside positive emotions such as pride and enjoyment. Conversely, extrinsic motivation, often associated with performance goals, can lead to anxiety and surface-level learning, particularly when driven by performance-avoidance goals and fear of failure (Pekrun, 2006). Studies in students' learning goal orientation in chemistry lecture-based courses indicated students were motivated both intrinsically and extrinsically. (Lewis, 2018; Naibert et al., 2024) While these studies have explored motivational patterns in lecture-based chemistry courses, there is limited understanding of how these dynamics play out in laboratory settings.

Aim

Our observations in the analytical chemistry laboratory course indicate that while some students dedicate significant effort and aim for excellence in mastering the analytical chemistry laboratory course, others are primarily driven by grades or prioritize merely completing tasks with minimal effort. Therefore, this study explored students' learning goal orientation in the analytical chemistry laboratory, using the Scales for Assessment of Learning and Performance Goals

(SELLMO-ST; Spinath et al., 2002). Grounded in achievement goal theory, SELLMO-ST measures four distinct orientations: learning, performance-approach, performance-avoidance, and work-avoidance goals. Learning is one goal orientation and is associated with intrinsic motivation and a focus on personal growth and understanding. Performance-approach goals emphasize outperforming others and receiving recognition, while performance-avoidance goals are driven by a fear of failure and avoiding appearing. The following research-questions were explored: (1) What are student learning goal orientations in the analytical chemistry laboratory? (2) What is the influence of gender on motivation profiles? (3) What difference in motivational patterns do students show between cohorts?

Method

Participants

The practical laboratory course for analytical chemistry is part of different science curriculums at an Austrian university. Participant students included first-year Chemistry (n = 71), third-year Molecular Biology (n = 84), second-year Environmental System Sciences (n = 47), and second-year pre-service Teacher Education (n = 14). Additionally, fourth-year students (n = 57) of the advanced analytical chemistry course took part in this study. Altogether, 273 students (58% female, 41% male and 1% diverse) participated in the study. The study was conducted with the approval of the university ethics committee and in accordance with established ethical guidelines. Participation was voluntary, and written informed consent forms from the students were collected. SELLMO-ST questionnaire return was > 95%.

Learning Goal Orientation

The student version of the Scales for the Assessment of Learning and Performance Goals (SELLMO-ST; Spinath et al., 2002) was used to evaluate academic goal orientations in the analytical chemistry laboratory courses. The SELLMO-ST instrument consists of 31 items, categorized into four scales starting with “In the analytical chemistry laboratory course, it is important for me…” : Learning (8 items, e.g., '... to learn something interesting'), Performance-approach (7 items, e.g., '... to get better grades than others'), Performance-avoidance (8 items, e.g., '... to hide if I know less than others'), and Work-avoidance (8 items, e.g., '... to finish my studies with little effort'). Items are rated on 5-point Likert scales ranging from "totally disagree" (1) to "totally agree" (5). Cronbach's alpha was 0.85 for the learning goal orientation scale, 0.84 for the approach-achievement, 0.89 for the avoidance-achievement and 0.89 for the work-avoidance scale, indicating good reliability. The SELLMO-ST questionnaire was administered in the analytical chemistry laboratory on the first day of each practical course. Answering the SELLMO-ST questionnaire took approximately 10 minutes. Data were analysed using IBM SPSS Statistics (Version 28).

Results & Discussion

(1) What Are Student Learning Goal Orientations In The Analytical Chemistry Laboratory?

Table 1 shows the descriptive statistics for the SELLMO-ST scales, assessing the different learning orientation goals in the analytical chemistry laboratory. Overall, the results show a highly pronounced learning orientation and, in comparison, less pronounced values for performance-approach, performance-avoidance, and work-avoidance.

This suggests that most students prioritize developing competence and understanding in their laboratory work, reflecting high levels of intrinsic motivation. Some students are motivated by external validation and competition in the laboratory setting, though it is not the primary driver

for most students. The low performance-avoidance goals score indicates that most students experience relatively low levels of anxiety-driven motivation. Further, the low work-avoidance score shows that most students are willing to engage actively in laboratory tasks. This is a positive outcome, as learning goals are typically associated with adaptive learning behaviours and deeper engagement (Ryan & Deci, 2000). Furthermore, recent research by Liu (Liu et al., 2025) underscores the intricate relationships between motivation, emotions, and academic success in chemistry education.

Table 1: Descriptive statistics SELLMO-ST Scales (1 low to 5 high).

SELLMO -ST Scale	Mean	SD	α
Learning Goals	4.32	.59	.85
Performance-Approach	2.76	.75	.84
Performance -Avoidance	2.22	.87	.89
Work-Avoidance	2.02	.86	.89

(n = 273). M (mean) and SD (standard deviation), Cronbach's α.

The relationship between the SELLMO-ST goal orientation scales is presented in Table 2. The learning goals scale strongly associated with positive motivational patterns, including a positive correlation with performance-approach goals, and a negative correlation with work-avoidance. This suggests that students focused on learning goals are less likely to avoid effort and may also seek some level of recognition. There was no significant relationship with performance-avoidance, indicating that fear of failure does not strongly align with intrinsic motivation. The performance-approach goals scale positively correlated with performance-avoidance goals, indicating that students driven by competition may also experience fear of failure. This could be interpreted as the risk of critic versus appreciation, which in turn could be met by the feedback-style from laboratory teachers. An expected weak positive correlation with work-avoidance, suggesting a minimal connection between competition-driven motivation and effort minimization. In contrary, fear-driven motivation is often linked to disengagement and reduced effort is reflected in the moderately correlation of performance-avoidance with work-avoidance.

Table 2: Bivariate correlation SELLMO-ST Scales of goal orientation.

SELLMO Scale	2.	3.	4.
1. Learning	.202 (<.001)	-.049 (.420)	-.388 (<.001)
2. Performance-Approach		.588 (<.001)	.091 (<.137)
3. Performance-Avoidance			.423 (<.001)
4. Work-Avoidance			-

Note: *r* (p)

(2) What Is The Influence Of Gender On Motivation Profiles?

Key findings from the descriptive statistics in Table 3 indicate that female and male students had comparable mean scores for learning goals. This similar motivation may arise from a shared enjoyment of the practical aspects of the laboratory course and the self-selection involved in university program enrollment. Additionally, no significant differences were observed between genders in performance-approach or work-avoidance scores, which may be attributed to the laboratory setting's emphasis on teamwork and collaboration, helping to minimize motivational variation. However, there was a significant difference on performance-avoidance goals between female and male students. This pattern may reflect a stronger fear of failure among female students. Addressing this issue could involve maintaining a supportive laboratory environment that fosters confidence and reduces anxiety, where students feel comfortable expressing ideas without fear of negative judgment, and emphasizing the learning process through meaningful feedback.

Table 3: Descriptive statistics SELLMO-ST Scales (1 low to 5 high) for genders .

	M (SD)			
	Learning	Performance-Approach	Performance-Avoidance	Work-Avoidance
Female (n = 158)	4.34 (.19)	2.81 (.81)	2.36 (.93)	2.02 (.93)
Male (n = 111)	4.28 (.52)	2.70 (.65)	2.01 (.71)	2.01 (.74)
$t(267)$ =	.912 p = .363	1.15 p = .253	3.28 p = .001	.067 p = .946

M (mean) and SD (standard deviation), t = independent sample t-test.

(3) What Difference In Motivational Patterns Do Students Show Between Cohorts?

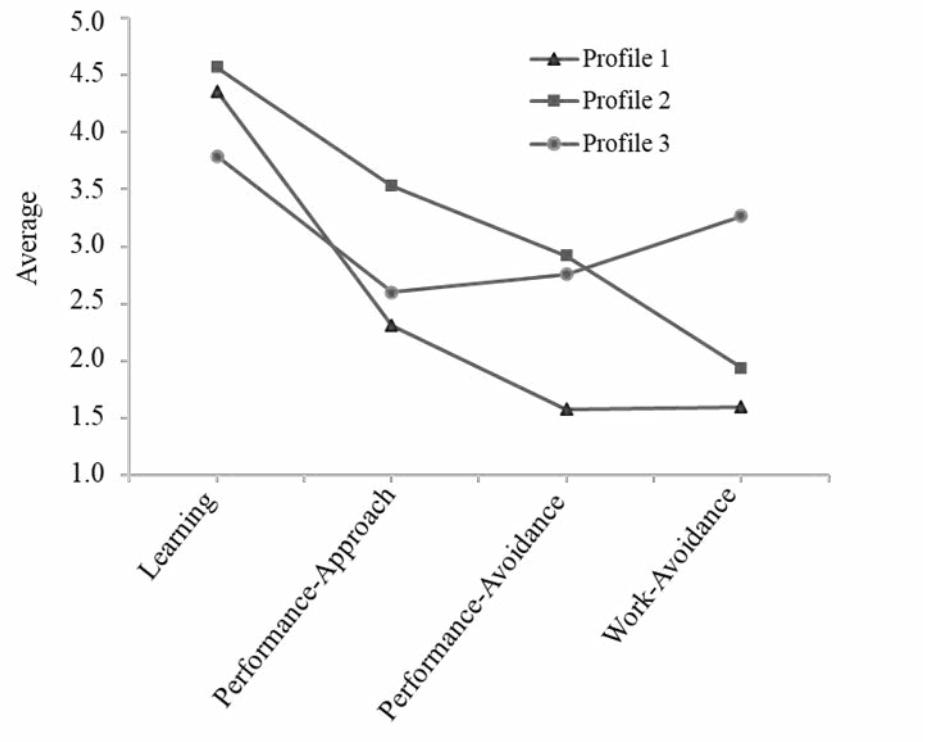
The motivational patterns from the five student cohorts are shown in Table 4. The key finding was between the Chemistry and Environmental Systems Sciences cohorts, where statistical differences were found for the mean scores for the learning scale ($t(116) = -2.73$, $p < .01$), performance-approach ($t(116) = -4.51$, $p < .001$), and performance-avoidance ($t(116) = -2.64$, $p = 0.009$), though not for work-avoidance ($t(116) = 1.68$, ($p = .096$). Suggesting less emphasis on competence and recognition in the analytical chemistry laboratory course, which may be influenced by the interdisciplinary focus of the Environmental Systems Sciences. These findings highlight the importance of tailoring laboratory experiences to student cohorts. Figure 1 shows three generated profiles (K-Means) from the student cohorts in the analytical chemistry laboratory. Profile 1 consist of 48,7% (n = 133), the second profile of 31,5% (n = 86), and the third profile of 19,7% (n = 54) students. The profile groups 1 and 2 show high learning goal orientation and low work-avoidance tendencies. Profile 1 demonstrates minimal influence from performance-oriented goals (either approach or avoidance) compared to profile 2, which shows moderate performance orientation. Profile 3 characterizes a high tendency to work-avoidance and performance-avoidance with a lower learning goal orientation compared to the other two profiles.

Table 4: Descriptive statistics SELLMO-ST Scales (1 low to 5 high) for student cohorts.

Student cohort	M (SD)			
	Learning	Performance-Approach	Performance-Avoidance	Work-Avoidance
Environ. System Sciences (n = 47)	4.03 (.62)	2.37 (.67)	1.90 (.70)	2.15 (.83)
Pre-Service Teacher (n = 14)	4.22 (.35)	2.60 (.76)	2.05 (.80)	2.70 (1.62)
Molecular Biology (n =84)	4.38 (.53)	2.79 (.79)	2.29 (.96)	1.84 (.77)
Chemistry (n = 71)	4.37 (.69)	2.95 (.68)	2.30 (.84)	1.89 (.83)
Advanced Analytical Chem. (4th year) (n = 57)	4.41 (.44)	2.80 (.72)	2.31 (.85)	2.13 (.69)

M (mean) and SD (standarddeviation)

Figure 1: Mean values of the learning goal orientation scales, learning, performance-approach, performance-avoidance and work-avoidance. Profile 1 (n = 133), Profile 2 (n = 86), Profile 3 (n = 54).



Conclusion

This study revealed that students in the analytical chemistry laboratory predominantly demonstrate intrinsic motivation, supported by strong learning goals, moderate performance-approach tendencies, and mostly low avoidance behaviors. This motivation may stem from the shared enjoyment of the practical aspects of laboratory course work and the students' self-directed choices in selecting their university programs. Gender differences revealed that female students experienced a stronger fear of failure, which could be addressed by maintaining a supportive laboratory environment and emphasizing the learning process through meaningful feedback. Additionally, the findings suggest that laboratory experiences for the interdisciplinary Environmental System Sciences cohort could be further refined to enhance meaningful learning by providing targeted feedback that emphasizes the relevance of laboratory tasks.

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Supporting First-Semester Chemistry Students: Development And Evaluation Of A Two-Phase Digital Learning Unit In Redox Chemistry

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STEM degree programs, such as chemistry, are associated with a range of challenges, with mathematical content areas posing particularly significant difficulties for students (e.g., Averbeck et al., 2018; Seymour & Hunter, 2019; Ye et al., 2024). However, in the context of redox chemistry, such content is fundamental to achieving a deeper understanding of chemical relationships.

This project aims to develop, implement and evaluate a two-phase digital learning unit designed to support first-semester chemistry students in understanding mathematical-chemical concepts and tackling related tasks in redox chemistry. In the first phase, students engage independently with interactive educational videos. In the second phase, they work on exercises and are provided with one of three different digital support measures.

The effectiveness of the intervention will be analysed primarily in terms of improvements in content knowledge. Additionally, student evaluations regarding the attractiveness and usability of the learning unit as well as cognitive load will be considered. Other aspects included in the evaluation are logfile analysis, students' written assignments, and video recordings of the training phase.

Keywords: Higher Education, Postsecondary Education, Undergraduate Teaching

Introduction

Chemistry is considered one of the most challenging subjects for students at university (e.g., Childs & Sheehan, 2009). This is evidenced by the high dropout rates reported internationally in STEM degree programmes such as chemistry, which show a rising trend. Academic performance issues disproportionately often lead to early dropouts (e.g., Heublein et al., 2022; Seymour & Hunter, 2019).

Students enter higher education with diverse initial conditions, such as varying levels of prior knowledge and mathematical skills. However, these factors are among the key determinants of subsequent learning success (Averbeck et al., 2018). The content covered during the first semester forms the foundation for learning as part of a cumulative acquisition of knowledge. Consequently, there is an acute need for targeted measures to support first-semester students in mastering subject-specific challenges.

Thematic areas with high mathematical components appear to present particular difficulties for first-year students (Hoban et al., 2013; Potgieter et al., 2008; Ye et al., 2024). These include redox chemistry, which is taught in the first semester. Topics such as balancing redox reaction equations and applications of the Nernst equation are especially challenging (Potgieter et al., 2008). This is emphasised by numerous misconceptions and difficulties documented in the literature (see overviews by Duit, 2009; Horton, 2007). These include, for example, the concept of oxidation in general, difficulties identifying reducing and oxidising agents (e.g., Brandriet & Bretz, 2014), misinterpretation of oxidation numbers, and general struggles with setting up and balancing redox reaction equations (e.g., Potgieter & Davidowitz, 2011). Although extensive research highlights

learners' challenges in understanding redox chemistry, relatively few studies provide concrete suggestions for addressing these issues and evaluate their effectiveness (Goes et al., 2020).

Our objective is therefore to design, implement and evaluate a learning unit focused on redox chemistry that aims to help learners deal with their difficulties.

Research Design And Method

The developed two-week learning unit comprises two main phases. In the first phase, students engage with educational videos that have been designed according to research-based principles for maximising learning success (Kulgemeyer, 2020) and that have been enhanced with interactive *H5P* elements to promote active learning (e.g., Brame, 2016). They then attend two seminars, 135 minutes in total, where they work on exercises (training phase). During this time, the students are assigned to one of three different digital support measures. In a previously conducted qualitative study, the primary difficulties faced by first-semester students in redox chemistry were identified (Kneuper et al., 2025b). Based on these findings, worked examples (WE), flowcharts (FC) and brief solutions (BrS) were designed to help students deal with these difficulties in the training phase. It is important to emphasise that all students receive identical exercises in terms of content, and the allocated time for completing these tasks is consistent across all groups.

WEs present learners an experts' solution to a given problem, including the final answer. This allows students to understand and learn from this model approach (e.g., Atkinson et al., 2000). To encourage self-explanation (*self-explanation effect*) and promote the transition from learning with WEs to solving tasks independently, each thematic area includes a progression: an elaborated WE with self-explanation prompts, followed by a faded WE where learners complete specific solution steps independently, and finally open-ended tasks (e.g., Atkinson et al., 2000; Atkinson et al., 2003; Wittwer & Renkl, 2010).

FCs provide visual representations of workflows required to solve various problems or complete tasks and therefore serve as strategic tools (Işık, 2024; Yuriev et al., 2017). The FCs offered are structured around sub-goals and encourage procedural checks (Ye et al., 2024).

BrS show students the final answer, but do not provide any information or guidance on how to solve the problem/task. This enables them to check their solution, though they do not receive any process-related support. A more detailed description of the three support measures can be found in Kneuper et al. (2025a).

One focus of our research is to examine how the content knowledge of the students who take part in our study develops:

> Q1: To what extent do the educational videos affect the students' content knowledge?
>
> Q2: To what extent does the training affect the students' content knowledge, depending on the support measure offered?

Additional aspects investigated in this study, though not covered within this paper, include students' evaluations of the learning unit, the influence of personal variables on the development of content knowledge (e.g., gender or science motivation) and detailed analysis of students' interactions with WEs, FCs or BrSs.

To address Q1 and Q2, a knowledge test was developed that covers the conceptual basis of redox reactions as well as applications, such as reasoning with the Nernst equation. The test was validated through an ongoing exchange with the professor who gave the introductory chemistry lecture in the first semester. It consists of 27 multiple-choice single-select items (MC) and six

open-ended items. The MC items are internally consistent (α = .810), while a scoring scheme for the open-ended items is under development.

The content knowledge test is administered at three different times: at the beginning of the learning unit (pre), after engaging with educational videos (mid), and upon completion of seminar exercises (post). To answer question Q2, participants are assigned to one of three statistically comparable intervention groups based on their prior knowledge levels (pre-test content knowledge, MC items) and gender.

First Results of Iteration 1

In the winter semester 2024/25, a first iteration was conducted with $N = 90$ first-semester students (chemistry, chemical-biology and chemistry teaching), of whom 79 students (44 females, 34 males, 1 not specified) participated completely in the intervention and where therefore included in our analysis. Table 1 provides an overview of the initial results from the content knowledge test, addressing research questions Q1 and Q2. It should be noted that this analysis only considers the MC items; the evaluation of open-ended items is still pending.

Table 1. Development of the students' content knowledge (MC items) based on the intervention group (*$p < .001$).**

Group	Time	*n*	*M*	Mean Difference	Effect Size (part. η^2)	95%-CI
Worked Examples	pre	26	.437	.164***	.702	[0.104, 0.224]
	mid		.601			
	mid	26	.601	.105***		[0.051, 0.160]
	post		.707			
Flowcharts	pre	27	.420	.148***	.629	[0.091, 0.205]
	mid		.568			
	mid	27	.568	.019		[-0.026, 0.064]
	post		.587			
Brief Solutions	pre	26	.466	.127***	.499	[0.051, 0.202]
	mid		.593			
	mid	26	.593	.048		[-0.004, 0.101]
	post		.641			
All	pre	79	.441	.146***	.593	[0.111, 0.182]
	mid		.587			
	mid	79	.587	.057***		[0.028, 0.087]
	post		.644			

To examine the development of content knowledge within each group, a one-way ANOVA and post-hoc tests with Bonferroni-correction were performed separately for each group (WE/FC/BrS). The results are summarised in Table 1: Significant increases in content knowledge from 'pre' to 'mid' were observed across all groups, with large effect sizes. From 'mid' to 'post', significant improvements were detected exclusively in the WE group, whereas no significant changes were found for the FC and BrS groups.

Interaction effects between intervention groups (WE/FC/BrS) and time (pre/mid/post) on content knowledge development were determined by a mixed ANOVA with Greenhouse-Geisser correction. A significant interaction effect between time and group was detected with a moderate effect size ($F(3.70, 140.43) = 3.32$, $p = .015$, partial $\eta^2 = .080$). Table 1 shows that the increase in content knowledge from mid to post is highest in the WE group and lowest in the FC group, suggesting that the WEs are more effective in facilitating learning than the FCs.

Discussion & Outlook

The preliminary findings of this study indicate that the learning unit is well-suited for first semester students (see also Kneuper et al., 2025a) and that the educational videos are effective in supporting learning. Moreover, among the support measures compared, worked examples appear to be the most effective. A more detailed analysis is currently being carried out, incorporating the remaining content knowledge data (open-ended items), task processing data, generated logfiles, and video recordings from the training phase. To this end, appropriate coding manuals are being developed. Combining these sources of information is expected to provide valuable insights into developing effective learning opportunities for complex content areas in higher education. Furthermore, a second iteration in the winter semester 2025/26 is planned to increase the sample size.

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Representational Competence In The Context Of Electric Fields: An Eye-Tracking Study

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Multiple visual representations can significantly enhance learning and understanding of scientific concepts. However, for visual representations to be effectively used in learning, learners need representational competences, i.e. abilities to interpret and fluently coordinate multiple representations. Therefore, to design effective multi-representational learning materials, it is essential to understand representational competence and how learners retrieve and process information from visual representations. In this article, we present a study that explores representational competence in the context of electric field representations. In the study, 38 university science students completed a test including two different visual representations of electric fields, namely equipotential line diagrams and field line diagrams. In each task, they were asked to evaluate characteristics of the electric field shown, with some tasks requiring inter-representational coherence formation and others not. During task completion, students' eye gaze was recorded. Analyses revealed that while students demonstrated strong visual understanding of individual representations, they struggled to integrate these representations as shown by low response accuracy and confidence while perceiving high item difficulty and indicating high cognitive invest. Moreover, initial conclusions about students' visual strategies for handling the representations could be revealed.

Keywords: Non-Verbal Representations, Eye-Tracking, Process Skills

Theoretical Background

Visual representations play a crucial role in science and science education. Being able to use and switch between different representations is essential for understanding scientific concepts (Rau, 2017). However, to truly benefit from visual representations in learning, students need representational competences—knowledge and skills required to use visual representations for reasoning and problem-solving (Klein et al., 2017). These competences consist of two aspects: visual and connectional understanding (Rau, 2017). Visual competences involve intra-representational coherence formation, i.e. knowing how individual representations work, what information they convey, and how they connect to scientific concepts (Seufert, 2003). Connectional competences involve inter-representational coherence formation which incorporates the ability to connect and flexibly switch between different visual representations (Seufert, 2003).

Because visual representations are important in scientific communication, many researchers highlight the need to develop representational competences to help students grasp complex scientific ideas (De Cock, 2012; Rau, 2017). Therefore, numerous studies geared towards characterizing students' representational competences in science learning (e.g., Kohl & Finkelstein, 2005; Rau, 2018).

From the perspective of cognitive psychology, it is important to understand how learners retrieve information from one or multiple visual representations to design effective learning materials. Since these retrieval processes are difficult to observe directly, eye tracking, i.e. analysis of eye movements, provides valuable insights into how learners handle visual representations (Ubben et al., 2018). For example, in previous studies from science education research, analyses of gaze

behaviour revealed representation-specific visual strategies (Hahn & Klein, 2025) and processes of information extraction from different representations (Susac et al., 2023).

The Present Study

This study focuses on visual representations of electric fields, specifically equipotential line diagrams and field line diagrams. Equipotential line diagrams represent the electric potential, and field line diagrams depict the electric field, i.e. its magnitude and direction (Figure 1). Previous research identified numerous learning difficulties related to the interpretation of such electric field representations (Bollen et al., 2017; Campos et al., 2023, Küchemann et al., 2021). For instance, students confused characteristics of field lines and equipotential lines, and they failed to recognize field line density as an indicator of the field's magnitude (Bollen et al., 2017). Since electric field representations are crucial in undergraduate physics, understanding representational competences is key to developing multi-representational learning materials.

Research Aims

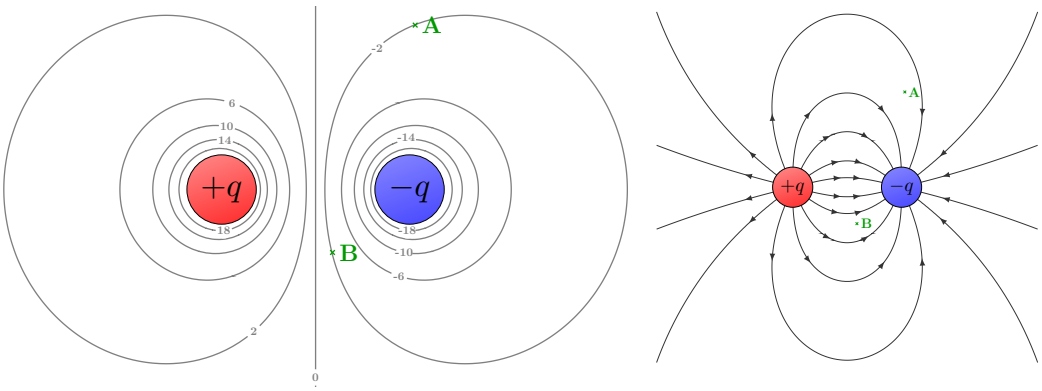
The current study takes an exploratory approach to investigate students' representational competences in using electric field representations. The following objectives are focused: (1) characterizing students' ability—their visual and connectional understanding—to handle electric field representations and (2) identifying visual strategies employed by students when processing electric field representations. To achieve these objectives, the study triangulates gaze data during representation processing and performance measures, i.e. students' response accuracy, response confidence, and perceived item difficulty.

Design And Methods

The study involved 38 university science students (20.9 ± 2.1 years, 68% male), most of whom were pursuing bachelor's or master's degrees in physics (3.5 ± 2.3 semester of study). Almost all participants were currently enrolled in or had taken a course on electrodynamics (95%). In the study, students completed a test on electric field representations, judging the magnitude, direction, and potential of fields shown as equipotential or field line diagrams. Some tasks required inter-representational coherence formation (e.g., judging electric potential using a field line diagram; in the following referred to as inter-representational coherence formation items), while others required interpretation within the same representation (intra-representational coherence formation items; Figure 1). The test included three scenarios commonly encountered in undergraduate electrodynamics courses, namely a point charge near an uncharged metallic plate, a symmetrical dipole (Figure 1), and an unsymmetrical dipole. After completing a task, participants moved to the solution page and provided their solution as well as a retrospective think-aloud explanation of their reasoning. Additionally, students rated their response confidence and the perceived difficulty of each item. During test assessment, students' gaze behavior was recorded using a Tobii Pro Fusion eye tracker (sampling frequency 120 Hz).

The following analyses focus on the symmetrical dipole scenario (Figure 1). To evaluate students' representational competences, response accuracy, response confidence, and perceived item difficulty were compared between intra- and inter-representational coherence formation items. These comparisons were conducted for tasks involving equipotential and field line diagrams of the symmetrical dipole, addressing the field's magnitude and potential. Moreover, gaze data during task processing was analysed by referring to the fixation count on the diagram. For analyses, performance measures and gaze metrics were subjected to non-parametric paired comparison analyses. Pearson correlation coefficient r and odds ratio OR are referred to as measures of effect size by following the interpretation of Cohen (1988).

Figure 1. Equipotential line diagram (left) and field line diagram (right) of a symmetric dipole (positive charge $+q$, negative charge $-q$). Two tasks were posed for each diagram: "Decide in which of the indicated points, A or B, (1) the electrical potential / (2) the magnitude of the electric field is higher". For the left diagram, the first question involves intra-representational coherence formation, while the second question requires imagining the corresponding field lines (inter-representational coherence formation item). For the right diagram, those task requirements apply vice versa. The points A and B are identically placed in all diagrams, ensuring isomorphic representations. While the electric field's magnitude is higher at point B (higher field line density), both points share the same electric potential.



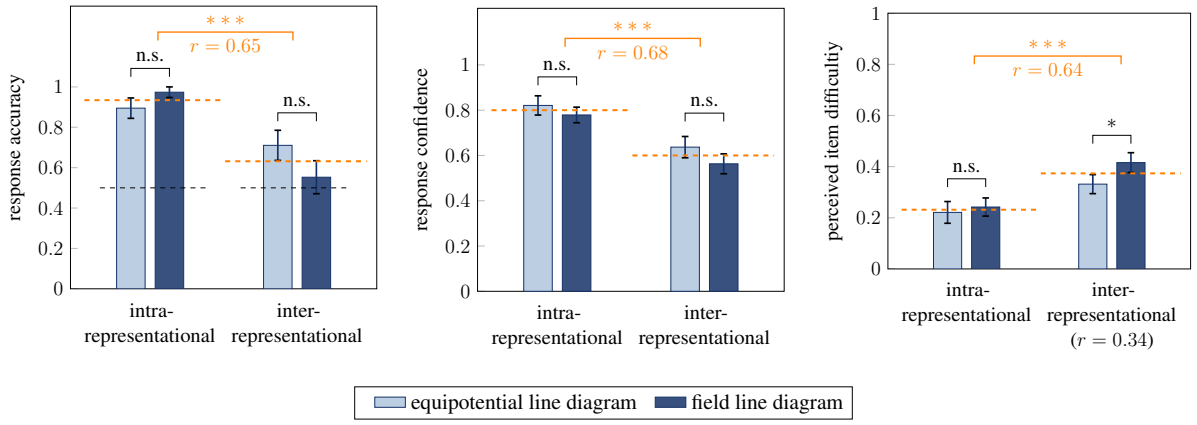
Results

When comparing students' response accuracy between intra- and inter-representational coherence formation items of the symmetrical dipole, a large-sized effect was observed ($z = -4.01$, $p < 0.001$, $r = 0.65$; Figure 2 left, orange). Students achieved lower scores on the inter-representational coherence formation items (0.63 ± 0.38) compared to the intra-representational coherence formation items (0.93 ± 0.17).

Regarding students' response confidence and perceived item difficulty of the symmetrical dipole scenario, similar effects were observed (Figure 2 middle and right, orange). For inter-representational coherence formation items compared to intra-representational coherence formation items, students were less confident in their answers ($z = -4.18$, $p < 0.001$, $r = 0.68$) and reported higher item difficulty ($z = 3.93$, $p < 0.001$, $r = 0.64$), with large effect size, respectively. Notably, students found it more challenging to judge the field's potential using the field line diagram than to determine the field's magnitude from the equipotential line diagram ($z = -2.07$, $p = 0.039$, $r = 0.34$), representing a medium-sized effect.

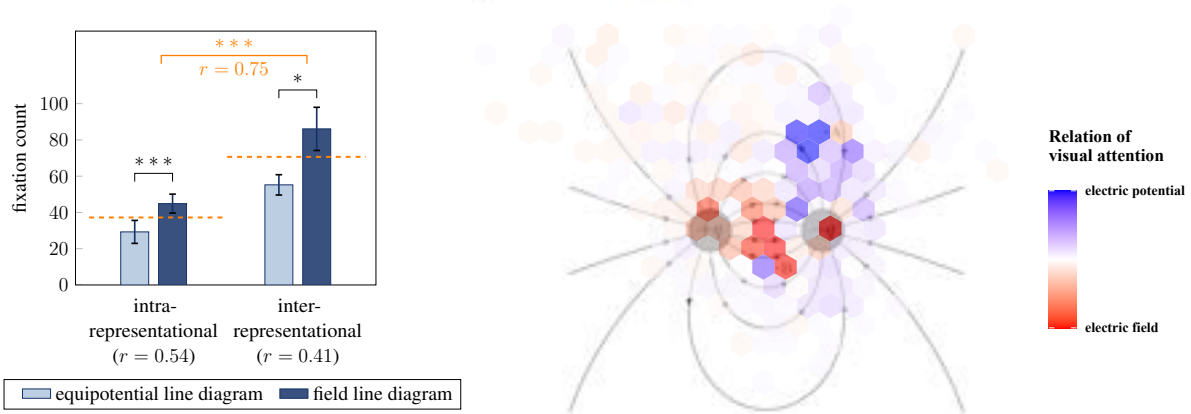
Gaze data analyses revealed that students fixated more often on the diagrams during inter-representational coherence formation items compared to intra-representational coherence formation items ($z = 4.63$, $p < 0.001$, $r = 0.75$), with large effect size (Figure 3 left, orange). Across both item categories, students showed significantly higher fixation counts for tasks involving the field line diagram than for those with the equipotential line diagram ($z = -3.29$, $p < 0.001$, $r = 0.54$ for intra-representational coherence formation items; $z = -2.52$, $p = 0.012$, $r = 0.41$ for inter-representational coherence formation items), with large and medium effect size, respectively.

Figure 2. Students' response accuracy (left), response confidence (middle), and perceived item difficulty (right) for symmetrical dipole items. Performance indicators are compared between intra-representational coherence formation items and inter-representational coherence formation items (means for both item categories in orange) using sign tests for response accuracy and Wilcoxon signed-rank tests for response confidence and perceived item difficulty. Comparisons between items involving equipotential line diagrams and field line diagrams are conducted using McNemar tests for response accuracy and Wilcoxon signed-rank tests for response confidence and perceived item difficulty (∗ / ∗∗∗ / n.s. statistical significance $p < 0.05$ / $p < 0.001$ / not significant, effect size r, black dashed lines indicate guessing probability, error bars represent 1 SEM).



When the equipotential line diagram of the symmetrical dipole was presented, response accuracy did not differ between the intra- and the inter-representational coherence formation task ($p = 0.07$). However, students allocated significantly more visual attention to the equipotential line diagram when evaluating the field's magnitude compared to its potential ($z = -3.87$, $p < 0.001$, $r = 0.64$).

Figure 3. Students' fixation counts on the diagrams for symmetrical dipole items (left) and visual attention difference pattern when processing the field line diagram (right). Left: Fixation counts are compared between intra-representational coherence formation items and inter-representational coherence formation items (means for both item categories in orange) and between items involving equipotential line diagrams and field line diagrams using Wilcoxon signed-rank tests (∗ / ∗∗∗ statistical significance $p < 0.05$ / $p < 0.001$, effect size r, error bars represent 1 SEM). Right: Hexagons illustrate differences in students' visual attention when analysing electric potential (blue) versus field magnitude (red) in the field line diagram. Colour intensity represents the magnitude of attention difference between the two tasks.



In contrast, when students were shown the field line diagram of the symmetrical dipole, students achieved significantly lower scores (0.97 ± 0.16 versus 0.55 ± 0.50; $\chi^2(1,38) = 12.50$, $p < 0.001$, $OR = 17$) and fixated significantly more often on the diagram ($z = -3.93$, $p < 0.001$, $r = 0.64$) when they judged the field's potential compared to its magnitude. Students' gaze patterns also revealed task-specific attention distribution within the field line diagram (Figure 3 right). When determining the field's magnitude, students predominantly focused on the charges and the field lines surrounding point B. Conversely, when assessing the field's potential, their attention was directed toward point A and the area around the negative charge.

Discussion And Outlook

When handling electric field representations, students demonstrated lower response accuracy, reported lower confidence, perceived higher item difficulty, and allocated more visual attention to the representations when inter-representational coherence formation was required compared to items that involve intra-representational information extraction. These findings align with frameworks from cognitive psychology that distinguish between two facets of representational competences: visual understanding of a single representation and connectional understanding of different representations (Rau, 2017; Seufert, 2003).

In the context of electric fields, these results suggest that students possess strong visual understanding of equipotential and field line diagrams. Contrary to prior studies, no difficulties in associating field line density with the field's magnitude were observed (Bollen et al., 2017). Instead, students exhibited targeted focus on the field lines around the point with higher field magnitude. Moreover, nearly all students correctly judged the field's magnitude from the field line diagram, which implies that their visual strategies were guided by top-down processes rather than by surface features of the diagram, indicative of advanced visual expertise.

However, consistent with earlier research on electric fields, students encountered significant challenges in connectional understanding (Campos et al., 2023). Specifically, when tasked with assessing the field's potential from a field line diagram, their performance was hardly above guessing probability, they reported high item difficulty and showed high cognitive invest. While students performed well in judging the field's magnitude from a field line diagram, these findings suggest a specific lack of representational competence in relating field lines to electric potential. To shed light on students' difficulties and reveal expertise characteristics, further analyses will focus on students' reasoning and comparisons between high- and low-achieving students.

Funding

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Improving Problem-Solving Skills Using Entrepreneurial STEM Intervention

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This study aims to provide an example for potential future interventions in the context of entrepreneurship and sustainability and enhance problem-solving skills with an entrepreneurial STEM intervention. Fourteen senior pre-service chemistry teachers (PTs) worked in five small groups, each developing a distinct STEM project (e.g., making soap from used cooking oil). For each project, the groups were required to identify relevant Sustainable Development Goals (SDGs) and prioritize social entrepreneurship. Data was collected using the Interpersonal Problem-Solving Inventory (pre and post) and PTs' reflection forms (post). The quantitative data indicated that the implemented STEM activity significantly impacted the sub-dimensions of negative approach to interpersonal problems, low self-confidence, and unwillingness to take responsibility in PTs' interpersonal problem-solving skills. The qualitative data pointed to the changes in participants' capability of making connections between chemistry and everyday life. PTs have stated that they have gained valuable experience in laboratory practice and project writing, both of which would contribute highly to their career. In addition, some of the PTs have stated that the intervention improved their entrepreneurial skills. Lastly, the study contributes to the field by bringing authenticity to STEM education by incorporating social and green entrepreneurship and supporting students' problem-solving skill development.

Keywords: *Entrepreneurial STEM, problem-solving, social entrepreneurship*

Introduction

Recently, STEM education has begun to focus on various topics, including sustainability and entrepreneurship. When the research on entrepreneurship is reviewed, it is commonly viewed as financial entrepreneurship in education rather than other types, such as social, innovative, and sustainable entrepreneurship. While financial entrepreneurship focuses on monetary expectations through performing different activities such as starting a business and selling a product or a service with profit (Hisrich & Peters, 2002), social entrepreneurship focuses on social change and cultural issues rather than monetary expectations (Barberá-Tomás et al. 2019), and green entrepreneurship focuses on solving environmental problems using sustainable processes (QAA, 2018). Currently, the integration and implementation of entrepreneurship in STEM education is a new area with a limited number of studies. The current study aims to integrate enterprise education and STEM education while promoting social and green entrepreneurship. Enhancing entrepreneurial STEM education is important because entrepreneurial thinking and practices are essential for fostering sustainable, collegial, and collaborative interactions that enable innovative STEM practices (Abd-El-Khalick et al., 2011). One of the common features of STEM education and entrepreneurship is their focus on generating solutions to real-life problems. In this regard, entrepreneurial skills such as problem solving and creativity play a crucial role in enhancing the understanding of the relationship between STEM and real-world contexts (Bicer et al., 2017; Sarı et al., 2022; Kaya-Capocci et al., 2024). Moreover, although there are studies indicating that entrepreneurial STEM activities positively affect students' problem-solving skills, there is a need for an increase in the number of such studies (Sarı et al., 2022; Kaya-Capocci et al., 2024). This study investigated the effects of Entrepreneurial STEM activities on students' problem-solving skills through the implementation of activities structured according to the nine-step Engineering Design Process proposed by Hynes et al. (2011). Previous research highlights Engineering Design

Process–based STEM practices as effective pedagogical tools for fostering 21st-century skills, including problem-solving abilities (Hacıoğlu et al., 2016), and for enhancing students' conceptual understanding (Tatlı, 2022).

Methodology

The research questions (RQs) of this study are:

1. How do PTs' problem-solving skills change following an entrepreneurial STEM intervention?

2. What do PTs think about the effectiveness of the intervention they've completed?

Participants

This study was conducted as part of a lesson titled "Service to Community" at a public university during the first semester of the 2024-2025 academic year. Fourteen PTs participated in the study.

Research Tools

While PTs' reflection form (post) was used to collect qualitative data, the Interpersonal Problem-Solving Inventory (pre and post) was used to collect quantitative data.

Interpersonal Problem-Solving Inventory (PSI)

The scale was developed by Çam and Tümkaya (2007) to assess interpersonal problem-solving skills. The scale consists of 50 items and yielded a five-factor solution: Negative approach to interpersonal problems, Constructive approach to interpersonal problems, Low self-confidence, Unwillingness to take responsibility, and an Insistent-persevering approach. It has been determined that the inventory applies to university students between the ages of 18 and 30. While the Cronbach's alpha internal consistency values of the subscales ranged from .67 to .91, the test-retest stability coefficients varied from .69 to .89.

Reflection Form

Following the completion of the intervention, the pre-service teachers (PTs) individually completed a reflection form. The form included two open-ended questions designed to explore their perceptions and experiences regarding the intervention (see Table 5). The questions were reviewed by two field experts to ensure their comprehensiveness and appropriateness.

Intervention

The intervention was conducted over 12 weeks during the first semester of the 2024–2025 academic year. After completing the PSI, the pre-service chemistry teachers (PTs) were organized into small groups and asked to identify problem situations related to the United Nations' Sustainable Development Goals (SDGs). The Sustainable Development Goals (SDGs) addressed by Group 1 are presented in Table 1. During the intervention, each group developed a distinct social entrepreneurship–oriented STEM project. The projects were: (1) Sustainable Soap Production from Used Cooking Oil, (2) Removal of Heavy Metals from Simulated Water Using Eggshell Powder, (3) Bioplastic Protective Face Masks from Banana Peels, (4) Eco-Friendly Soap Sheets, and (5) Smart Edible Films and Coatings with Natural Spoilage Indicators. The problem scenarios of the five social entrepreneurship projects are presented in Table 2. In addition, the learning objectives of the Group 1 project are provided as an illustrative example in Table 3.

Throughout the implementation of the STEM activities, students followed the nine-step Engineering Design Process proposed by Hynes et al. (2011), which includes: (1) problem identification, (2) problem research, (3) generation of possible solutions, (4) selection of the most appropriate solution, (5) prototype development, (6) testing and evaluation, (7) sharing and

reflection, (8) redesign, and (9) finalization. After the intervention, all PTs completed the PSI again and submitted reflective forms.

The SDGs related to Group 1's project are presented in Table 1.

Table 1. SDGs of Group 1's Project.

No	Goal(s)
4	Quality Education (Target 4.7)
6	Clean Water and Sanitation (Target 6.3)
12	Responsible Consumption and Production (Target 12.4 & 12.5)
14	Life Below Water (Target 14.1)

Table 2. Groups' Social Entrepreneurship Interventions and Identified Problems.

Grup	Project Titles and Problem Statements
1	Sustainable Soap Production from Used Cooking Oil This project aims to produce an environmentally friendly cleaning product by recycling used cooking oil, thereby reducing water pollution and promoting sustainable waste management practices
2	Removal of Heavy Metals from Simulated Water Using Eggshell Powder The project focuses on mitigating the risks of heavy metal contamination in wastewater by employing waste eggshells as an eco-friendly, low-cost, and sustainable adsorption material.
3	Bioplastic Protective Face Masks from Banana Peels This project aims to reduce environmental pollution caused by disposable face masks by producing biodegradable bioplastic protective face masks from waste banana peels as a sustainable alternative.
4	Eco-Friendly Soap Sheets The project focuses on developing portable, biodegradable soap sheets as a sustainable alternative to conventional wet wipes, thereby reducing environmental pollution and promoting responsible consumption.
5	Smart Edible Films and Coatings with Natural Spoilage Indicators The project focuses on developing biodegradable edible films and coatings integrated with natural indicators to monitor the spoilage of meat and meat products, thereby enhancing food safety and reducing packaging-related environmental impacts.

Table 3. Learning Objectives of the Group 1 Project

Subject Disciplines	Learning Objectives
Chemistry	- Explain acid–base reactions.
Technology	- Provide examples of interdisciplinary applications of computational thinking.
Mathematics	- Determine an unknown quantity when the ratio of two quantities is given.
Engineering	- Develop and use sketch drawings to support idea generation and problem-solving during the engineering design process. - Gather qualitative and quantitative experimental data. - Document and analyse observations.
Social Entrepreneurship	- Recognize the role of interpersonal communication in social entrepreneurship. - Analyse the social responsibilities of entrepreneurs. - Propose strategies for spreading knowledge, products, and services for societal benefit.

Data Analysis

Quantitative data were analysed using the SPSS 22 package program. The Wilcoxon test was applied separately for each of the five sub-dimensions of the Interpersonal Problem-Solving Inventory. For a significant difference between the pre-test and post-test, the sigma value must be less than 0.005.

The qualitative data were analysed through content analysis. The codes were developed by two researchers. Each form was assigned a code by researchers individually, and these codes were compared to see whether there would be any disagreements. Through these discussions, the variance of 2% between the coders was resolved. The inter-rater reliability for the coding is 98%. The initial letters ‘PT’ and a number from 1–14 was given to each preservice teacher (i.e., PT-16).

Findings

The current study revealed the following findings related to the RQs, respectively.

RQ1—Investigating PTs’ Problem-Solving Skills

In the inventory, which consists of five sub-dimensions, each sub-dimension was separately subjected to the Wilcoxon test, and sigma values were obtained (see Table 4). When examining the sigma values, it was found that the intervention created a significant difference in the sub-dimensions of the Negative approach to interpersonal problems, low self-confidence, and unwillingness to take responsibility. However, it did not create a significant difference in the sub-dimensions of constructive approach to interpersonal problems and insistent-persevering approach.

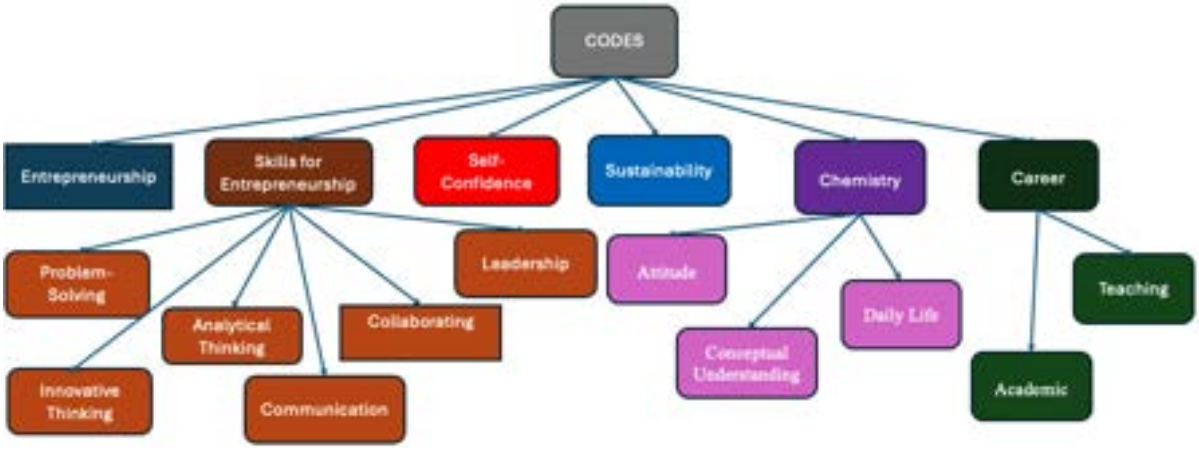
Table 4. The sub-dimensions and sigma values.

The Sub-dimensions	Asymp. Sig. (2-tailed)
Negative approach to interpersonal problems	0.001
Constructive approach to interpersonal problems	0.182
Low self-confidence	0.002
Unwillingness to take responsibility	0.004
Insistent-persevering approach	0.889

RQ2—Investigating Pts' Experiences And Feelings Of The Intervention

To respond to RQ2, PTs' opinions about the intervention were investigated through interview questions, and their opinions were classified under six major codes (see Figure 1 and Table 5).

Figure 1. Concept map for the codes of the study.



The results showed that the intervention strengthened PTs' entrepreneurship potential and the different skills necessary for Entrepreneurship. Besides, some PTs believed that the intervention helped improve their self-confidence. In addition, approximately 25% of PTs stated that the intervention improved their understanding of chemistry, attitudes toward chemistry, and their sustainability awareness by helping them to make connections with the world. Figure 3 shows that problem-solving is the most developed skill (see Figure 3). Furthermore, most of the PTs believed that this intervention was helpful to promote their future careers in both academic and teaching means (see Figure 4).

Table 5. Reflection forms' questions & example excerpts.

• **Interview Questions**
• What are your opinions about the effectiveness of the project you were involved in? • Do you think this project will be helpful later in your career?
Entrepreneurship *"These experiences have encouraged me in what I can achieve in Entrepreneurship. I will continue to take part in entrepreneurship interventions in the future that both generate financial and social benefits (PT-4)*
Skills for Entrepreneurship & Self-confidence • **Problem-Solving** *"The project improved my problem-solving skills, now I am more adept at using search engines and I am better at researching." (PT-1)* • **Collaboration** *"This project improved my teamwork and collaboration skills" (PT-10)* • **Innovative Thinking & Analytical Thinking** "*Trying to find solutions to environmental problems has improved my innovative and analytical thinking skills*" (PT-10) • **Communication & Leadership & Self-confidence** *"In this project, I was the team leader, in this way, I improved my communication and leadership skills and increased my self-confidence (PT-10)*
Sustainability "*Seeing that we can contribute to the environment by repurposing waste materials has increased my interest in and awareness of sustainability. In the future, I am to take part in interventions that focus on developing more sustainable solutions.*" (PT-9)
Chemistry • **Attitude & Conceptual Understanding & Daily Life Connection** "*Realizing the chemical properties of the eggshells makes chemistry more real and meaningful for me. I realized how effectively the eggshells we usually dispose of can be used in addressing the significant use of removing heavy metal accumulations, that pose a risk to human health. This allows me to use chemistry in my daily life, and this allows me to recognize I enjoy this subject. Once again, we learned new elimination methods for pollution, such as phytoremediation".* (PT-9)
Career • **Academic Experience** "*This project provided me with the opportunity to conduct scientific research. In this regard, I believe it has contributed to my academic and career development." (PT-10)* • **Teaching Experience & Sustainability** *"The knowledge I've gained in this experience will be useful in my teaching life. For example, I can teach my students about making soap from used cooking oils, as well as about information on sustainability." (PT-8)*

Figure 2. Percentage of codes for the first question from the form.

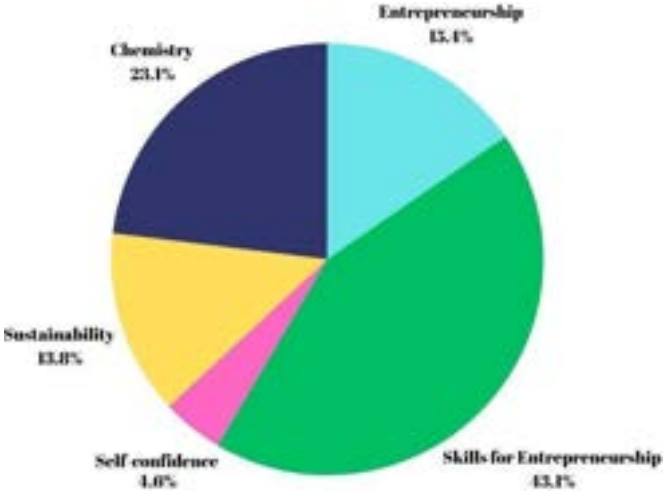


Figure 3. Percentage of sub-categories for "Skills for Entrepreneurship".

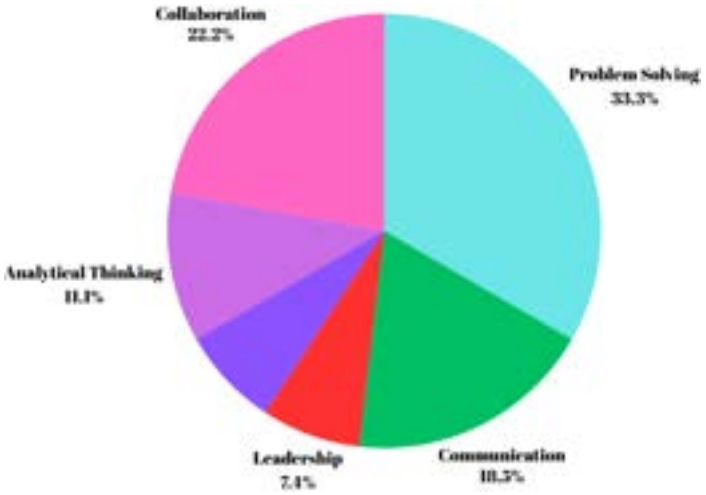


Figure 4. Percentage of codes for the second question from the form.



Discussion & Conclusion

The study aimed to increase PTs' problem-solving skills within the context of entrepreneurial STEM education. In the current study, qualitative data showed that 33.33% of PTs believed the effectiveness of the intervention to improve their problem-solving skills. A review of the literature on educational research reveals that studies examining problem-solving skills have generally focused on no more than three sub-dimensions (Kaya-Capocci et al., 2024). However, in the present study, the Interpersonal Problem Solving Inventory developed by Çam and Tümkaya (2007), which conceptualizes problem-solving skills across five sub-dimensions and considers three sub-dimensions insufficient for an in-depth analysis, was employed. This approach enabled a more comprehensive examination of the effects of Entrepreneurial STEM activities on problem-solving skills across five distinct sub-dimensions. Examining the results of the interpersonal problem-solving inventory, which constitutes the quantitative data, a significant difference was observed in three out of the five sub-dimensions, while no significant difference was found in the other two. The sub-dimensions with a significant difference were negative approach to interpersonal problems, low self-confidence, and unwillingness to take responsibility. The sub-dimensions without a significant difference were constructive approaches to interpersonal problems and an insistent-persevering approach. The negative approach to interpersonal problems dimension refers to intense negative emotions and cognitions, such as helplessness, pessimism, and sadness experienced when individuals encounter a problem (Çam & Tümkaya, 2007). The finding that STEM activities reduced PTs' negative perceptions toward problems supports the assertions of Topsakal et al. (2022). This positive shift may be attributed to students' learning how to systematically approach and solve problems by following the Engineering Design Process during STEM activities. The unwillingness to take responsibility reflects a reluctance to assume responsibility in problem-solving situations, while the low self-confidence dimension represents insecurity regarding one's ability to solve problems (Çam & Tümkaya, 2007). In the present study, positive changes were observed in both the unwillingness to take responsibility and low self-confidence sub-dimensions. These findings suggest that learning how to address a real-life problem within Entrepreneurial STEM activities may enhance PTs' self-confidence, enabling them to take greater responsibility in the problem-solving process.

The qualitative data also showed that some PTs believed that this intervention positively affected Entrepreneurship. Besides, they also stated the intervention was useful to improve some crucial skills (communication, leadership, innovative thinking, analytical thinking, and collaboration) and self-confidence, which are related to becoming and succeeding as an entrepreneur. In addition, it seems that the intervention presented here was effective in improving PTs' understanding of the chemistry topics and attitudes toward chemistry by helping them to make connections between real-world and chemistry knowledge. Lastly, we believe that the study is going to add a unique contribution to the related literature because it seems to be helpful to increase PTs' sustainability awareness.

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Part 20 / Strand 20

Methods and Methodological Aspects in Science Education Research

Co-editors: *Kason Ka Ching Cheung & Adrienne Lorelei Traxler*

Part 20 / Strand 20 Methods and Methodological Aspects in Science Education Research

Foundational aspects and debates of epistemology, ontology and axiology of methods and methodologies of science education research.

Sub-themes:

1) Qualitative Methods in Science Education Research
2) Quantitative Methods in Science Education Research
3) Mixed Methods Approaches in Science Education Research
4) Ethical Considerations in Science Education Research
5) Critical perspectives on methods and methodologies
6) Emerging technologies and Methodological Aspects in Science Education Research

Contents

Strand 20: Methods and Methodological Aspects in Science Education Research 1770

Measuring Classroom Network Dynamics with Temporal Exponential Random Graph Models 1771

The Critical Role of Pre-test Sensitisation and the Solomon Four-Group Design in Science Education Research: A Transition From Uncertainty to Necessity..... 1778

Strand 20: Methods and Methodological Aspects in Science Education Research

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Foreword

The strand Methods and Methodological Aspects in Science Education Research (or informally, "the methodology strand") is a slim but important part of the ESERA conference. Other strands employ a rich array of techniques and arguments in their studies, but for this strand, the primary focus is on the methods. Authors may use their work to showcase a methodological advance, to promote an existing technique to the community, or to invite critical discussion of their analysis structure and choices. Method is the key focus of this theme, while it can be integrated into a range of science education contexts set up in other themes.

In this year's proceedings, the methodology strand has two chapters. The first, by Sundstrom and collaborators, uses temporal exponential random graph models to quantify the existence and growth of structure in student collaboration networks in university science courses. The second, by El Karkri and collaborators, uses a Solomon Four-Group Design to probe for the effect of pre-test sensitisation in secondary school science courses. Both studies are quantitative in focus, and both recommend further use of their tools in the science education research community. Temporal network models allow for the adaptation of popular pretest/post-test designs to incorporate network effects, and the Solomon Four-Group Design gives principled attention to the often-neglected question of pretest effects that may damage the precision or reliability of findings.

Integrating advanced methodology and data analyses make an important contribution to science education issues. We envisage that these advanced methodological considerations will gain increasing attention among researchers who work in different issues and disciplines in science education. For instance, the temporal exponential random graph models, which show student networks in physics education research in this conference proceeding, will interest researchers in chemistry and biology education. The Solomon Four-Group Design, which attends to students' scientific reasoning in different experimental conditions in this proceeding, will interest scholars working on experimental design that advances students' nature of science and scientific practices. We believe that papers in this strand will extend our discussion on how to advance science education using methods. In the future, science education researchers will continually derive methodological frameworks based on the designs discussed in the two chapters. We thank the authors for their work, and look forward to the next stage in the conversation of methodological advances and practices in the field of science education research.

ESERA 2025 Copenhagen

Measuring Classroom Network Dynamics with Temporal Exponential Random Graph Models

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Interacting with peers has been shown to positively correlate with undergraduate science students' performance and sense of belonging. Correspondingly, a growing number of physics education research studies have examined patterns of peer interactions using social network analysis. Time-dependent student networks are of particular interest, as they illuminate the ways in which student communities form. Existing studies of time-dependent student networks, however, rely on descriptive measures and/or simple statistical tests that do not account for other variables that may explain classroom network dynamics. In this study, therefore, we demonstrate the use of temporal exponential random graph models (TERGMs), a form of multiple regression for time-dependent network data. We apply TERGMs to pre- and post-semester peer interaction networks from two introductory physics courses in the United States taught using different active learning pedagogies: Peer Instruction (i.e., small groups of students answer poll questions during lecture) and SCALE-UP (i.e., small groups of students work on problem solving and laboratory activities in a classroom specifically designed for group work). We find that students form connections with small groups of three peers in both courses. In SCALE-UP, however, students are also unlikely to form connections that create long chains. These results are not extractable from the descriptive network measures alone, suggesting that TERGMs (or other similar models) are necessary for measuring classroom network dynamics.

Keywords: Network Analysis, Collaborative Learning, Pedagogy

Introduction

According to the participationist framework, learning occurs as people engage with their surrounding community (Packer & Goicoechea, 2000). Collaborating with others allows for learners to revise upon their own thinking and co-construct understanding. In university-level physics classrooms in particular, researchers have demonstrated that social interactions with peers positively correlate with student outcomes such as academic performance, attitudes, and persistence (Bruun & Brewe, 2013; Dou et al., 2016; Zwolak et al., 2017).

Social network analysis (SNA) is an increasingly popular tool for analyzing peer interactions among physics education researchers (Grunspan et al., 2014). Many SNA studies administer a network survey to students, asking which peers they interact with about their physics course, at one point in time and use a combination of descriptive statistics, regression methods, and exponential random graph models (ERGMs) to make claims about patterns in the resulting interaction network (Bruun & Brewe, 2013; Commeford et al., 2019; Sundstrom et al., 2022b; Crossette et al., 2023; Pulgar et al., 2023). Other SNA studies examine how student interaction networks evolve over time by administering several network surveys throughout a physics course and analyzing changes in the resulting networks (Brewe et al., 2010; Bruun & Bearden, 2014; Commeford et al., 2021; Sundstrom et al., 2022a, Wolf et al., 2022). Such "time-dependent" student networks illuminate the ways in which student communities develop in a classroom and how classroom instruction may impact student network development.

The existing studies of time-dependent student networks, however, have exclusively relied on descriptive statistics (e.g., network density) and/or simple statistical tests (e.g., t-tests) to make claims. These methods are limited because they do not allow for hypothesis testing: they measure

the effect of one variable at a time without accounting for other variables that may explain why networks change over time. More sophisticated tools, therefore, are necessary to make more nuanced claims about time-dependent student networks.

In this study, we expand upon the SNA methods that have been applied in physics education research to meet the methodological needs of time-dependent networks described above. We use temporal exponential random graph models (TERGMs)–a form of multiple regression for time-dependent network data–to measure network dynamics in two university-level, introductory physics courses taught using different active learning pedagogies. We aim to address the following research question: What types of peer interaction network structures form in different active learning environments in physics?

Methods

Data Collection

We use data from two courses at different institutions in the United States that were collected as part of a prior research project (Commeford et al., 2021). The first was an introductory physics course at Drexel University containing 116 students. The course contained one combined lecture section and several smaller laboratory and recitation sections. The lecture component was taught in a large lecture hall using "Peer Instruction," where the instructor asked students to discuss and respond to clicker questions. The second was an introductory physics course at North Dakota State University containing 71 students. The course was taught using the "SCALE-UP" pedagogy, where all students were in one course section that blended lecture, laboratory, and recitation activities. The course took place in a large room designed for group work: there were several round tables where students sat, and whiteboards were placed along the perimeter of the room.

In each course, the instructor administered an online network survey at the beginning and end of the semester. Students responded to the following prompt: "Please choose from the list of people that are enrolled in your physics class the names of any other student with whom you had a meaningful interaction in class during the past week, even if you were not the main person speaking." Below the prompt was an alphabetized course roster with associated check boxes, from which students could select as many names as they wanted. For the Peer Instruction course, the pre- and post-survey had response rates of 42% and 58% of enrolled students, respectively. For the SCALE-UP course, the pre- and post-survey had response rates of 70% and 66% of enrolled students, respectively. Responses made by students who did not consent to participating in the research were excluded from our analysis.

Data Analysis

We created undirected networks using the survey responses, with nodes representing students and edges representing a reported interaction between two students (regardless of which student reported the interaction on the survey), to reduce possible impacts of missing data due to non-respondents. We calculated several descriptive measures for each network, as in prior work (Commeford et al., 2021), to characterize its structure:

- Density: the proportion of all possible edges in the network that we observed
- Transitivity: the number of two-paths (e.g., student A is connected to student B and student B is connected to student C) that are closed (e.g., students A and C are connected)
- Giant component: the number of nodes that are contained in the largest connected cluster of nodes.

We then applied TERGMs to the data to measure whether different network structures (e.g., transitivity) are more (or less) likely to form in our observed post-semester networks than we would expect if the pre-semester networks evolved randomly. We used separable TERGMs in particular, as they model two distinct processes of network evolution: (1) formation–the tendency for new edges to form over time and (2) persistence–the tendency for edges formed early on to remain in the network over time (Krivitsky & Handcock, 2014). In line with our research goal of identifying the types of network structures that form in active learning classrooms, we only examine the formation process in this study.

Table 1. Predictor variables included in TERGMs.

Variable	Description	R syntax
Edges	The number of edges in the observed network.	edges
Chains	The number of two-paths (e.g., student A is connected to student B and student B is connected to student C) that are open (e.g., students A and C are not connected).	gwdsp(decay=0.5, fixed=TRUE)
Transitivity	The number of two-paths (e.g., student A is connected to student B and student B is connected to student C) that are closed (e.g., students A and C are connected).	gwesp(decay=0.5, fixed=TRUE)
Degree Distribution	The distribution of the number of edges connected to each node.	gwdegree(decay=0.5, fixed=TRUE)

We ran one TERGM for each of the two courses using the predictor variables listed in Table 1 and the "tergm" package in R. We included these particular variables because we expected them to vary between the Peer Instruction and SCALE-UP classrooms based on prior work (Commeford et al., 2019; Commeford et al., 2021). For example, we expected that chains would be more likely to form in Peer Instruction classes, as students typically sit in long rows of chairs in stadium style lecture halls, than in SCALE-UP classes, where students work in small groups at a round table.

Both models exhibited sufficient goodness-of-fit: the observed networks and a set of networks simulated from the resulting models had similar structural properties (Hunter et. al., 2008).

Results

Figures 1 and 2 show the pre- and post- semester networks for the Peer Instruction and SCALE-UP courses, respectively. Table 2 contains descriptive measures for each network. The Peer Instruction network does not appear to change much over time. In both networks for this course, the majority of students are connected in the giant component, which contains a combination of chains and closed triangles. Quantitatively, the density and transitivity values are similar for the pre- and post-networks. The SCALE-UP pre-network contains some isolated small groups of students and a few edges that bridge together these groups. The SCALE-UP post-network, on the other hand, contains more edges (the density increases) and more strongly connected small groups (the transitivity increases) than the pre-network.

Figure 3 and Table 3 show the coefficient estimates for the TERGMs applied to the observed networks. Odds ratios that are greater (less) than one and significant indicate that the network structure represented by the predictor variable is more (less) likely to form in our observed network than we would expect if the pre-network evolved randomly.

Figure 1. Pre- (left) and post- (right) peer interaction networks for an introductory physics course taught using Peer Instruction. Nodes represent students and edges represent self-reported, in-class peer interactions.

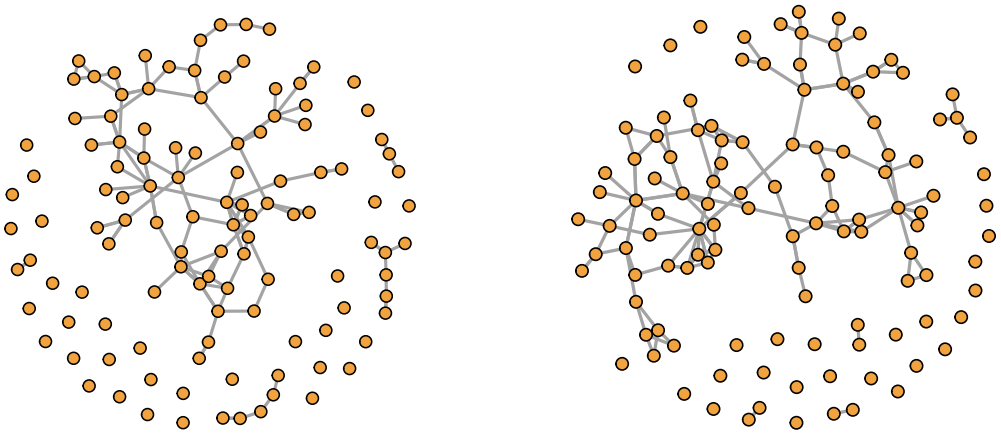


Figure 2. Pre- (left) and post- (right) peer interaction networks for an introductory physics course taught using SCALE-UP. Nodes represent students and edges represent self-reported, in-class peer interactions.

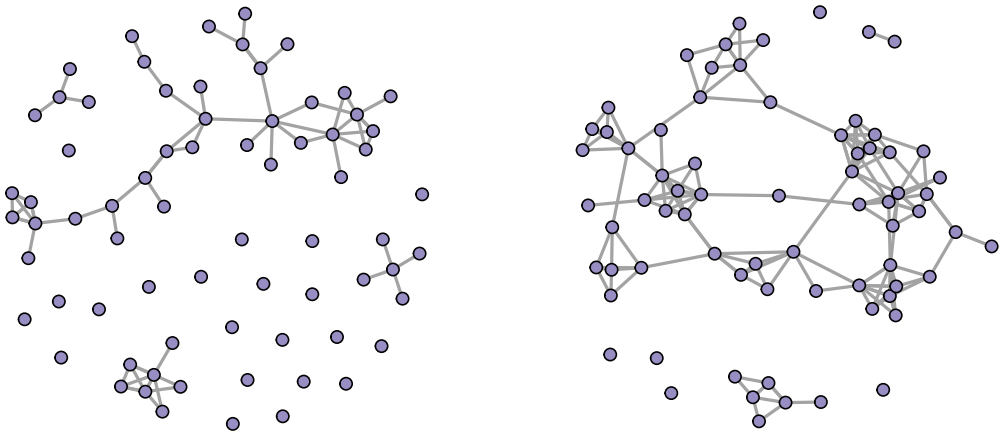


Table 2. Descriptive measures for the four networks.

	Peer Instruction		SCALE-UP	
	Pre	Post	Pre	Post
Nodes	116	116	71	71
Edges	135	159	71	176
Density	0.020	0.024	0.029	0.071
Transitivity	0.209	0.231	0.327	0.517
Giant component	67	80	34	58

In the Peer Instruction course, the only significant effect is transitivity: edges forming closed triangles are significantly more likely to form in our observed network than we would expect at random. Notably, this result is after controlling for the other effects included in the model and despite the raw transitivity values of the pre- and post-networks being similar (Table 2). The non-significant effect of degree distribution means that edges are not more likely to form if they create either a highly skewed degree distribution (i.e., with many students having few connections and a few students having many connections) or a very uniform degree distribution (i.e., with all students having a similar number of connections).

In the SCALE-UP course, we find that chains are significantly less like to form than we would expect at random and that edges that form closed triangles are significantly more likely to form than we would expect at random. Similar to the Peer Instruction course, we find no significant effect of degree distribution.

Figure 3. Coefficient estimates for TERGMs. Error bars represent 95% confidence intervals and asterisks indicate statistical significance (*$p < 0.001$).**

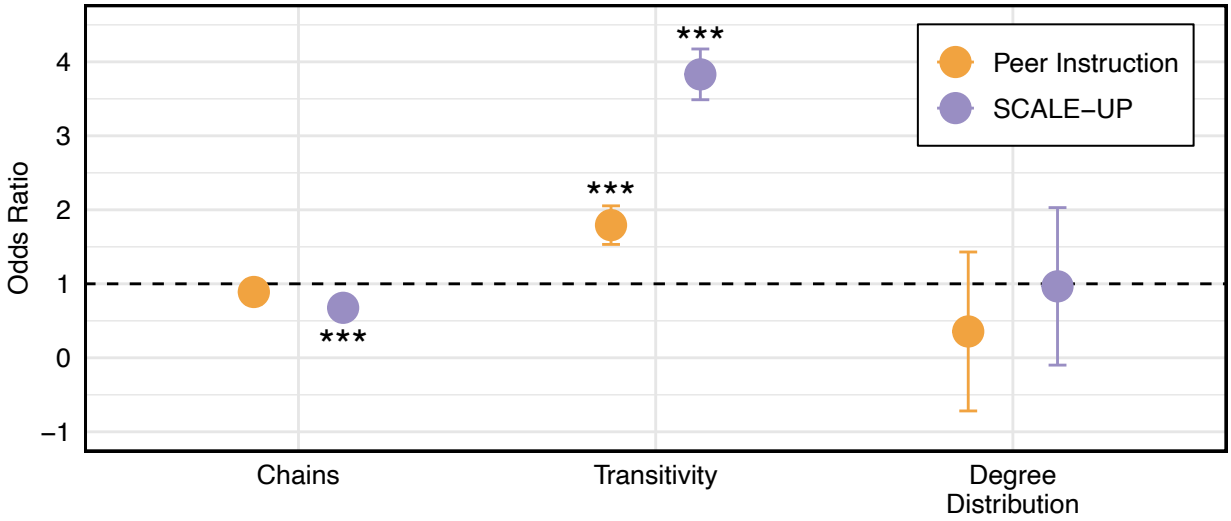


Table 3. Coefficient estimates for TERGMs. SE indicates standard error and asterisks indicate statistical significance (*$p < 0.001$).**

	Peer Instruction			SCALE-UP		
	Log-odds	SE	Odds ratio	Log-odds	SE	Odds ratio
Edges	-3.872***	0.653	0.021	-2.454***	0.559	0.086
Chains	-0.117	0.083	0.890	-0.392***	0.056	0.676
Transitivity	0.584***	0.133	1.793	1.343***	0.175	3.831
Degree Distribution	-1.033	0.548	0.356	-0.035	0.543	0.966

Discussion and Conclusion

We have characterized the dynamics of student networks using a statistical tool not yet applied in physics education research: temporal exponential random graph models. Results indicate

structural differences in the types of connections students form with their peers in two introductory physics courses taught using different active learning pedagogies. In a Peer Instruction course, students form connections with small groups of three peers. In a SCALE-UP course, students also form small group of three peers, but they are unlikely to form connections that create open chains.

We recommend for other education researchers to use TERGMs or similar models (e.g., stochastic actor-oriented models) when conducting time-dependent network studies, moving beyond descriptive and/or simple statistical approaches. In this study, for example, we found that after controlling for other effects in the model, some changes in network structure identified in the TERGMs differed from the descriptive statistics alone.

Acknowledgements

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ESERA 2025 Copenhagen

The Critical Role of Pre-test Sensitisation and the Solomon Four-Group Design in Science Education Research: A Transition From Uncertainty to Necessity

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Pre-test sensitisation (PS) is a critical concern in science education research, as it can influence participants' responses to interventions and potentially distort study outcomes. When students are pretested, they might gain insights or knowledge that allow them to answer correctly during subsequent assessments, thereby affecting the validity of the results (Pan & Carpenter, 2023). Two studies, undertaken a Spanish-Moroccan team of researchers, were conducted in secondary schools over two consecutive academic years (2021–2022 and 2022–2023), both utilising the Solomon Four-Group Design (SFGD) as a tool to detect PS (Campbell & Stanley, 1966; Solomon, 1949). Despite this shared framework, a notable divergence emerged in the results: the first study revealed no evidence of PS, while the second clearly shows sensitization. This difference led to new considerations and perspectives, raising essential questions about the role of PS in science education research. Should it be regarded as a prestigious methodological element, or is its inclusion always necessary? These findings challenge established perceptions and highlight the need for a critical reflect on the methodological significance of PS.

Keywords: Pre-test sensitisation, Solomon Four-Group Design, Quasi-experimental studies.

Theoretical Background

Numerous studies across different fields provide evidence supporting the presence of PS, demonstrating its impact on learning processes, attitudes, mental health interventions, and behavioural intentions (Hoogstraten, 1980; Lana & King, 1960; Spence et al., 2009; Spirito et al., 1988; Swanborn & De Glopper, 1999).

Conversely, many studies have reported the absence of PS, showing no significant effects on attitude change, behavioural measures, family interaction patterns, self-efficacy, or stress management scores (Jordaan et al., 2018; Kazdin, 1973; Lana, 1959; Parsons & Alexander, 1973; Rosa-Castillo et al., 2023; Rubel et al., 2010; Spence & Blanchard, 2001).

A nuanced perspective on pre-testing is offered by Hollins et al. (2023), who challenged the assumption that pre-testing universally enhances memory. Their findings suggest that pre-testing benefits are limited to specific guessed information, providing a more detailed understanding of its role in memory. Similarly, Pan & Carpenter (2023) demonstrated that the pre-questioning or pre-testing effect can enhance learning, even when initial tests include incorrect answers, through the use of various educational materials.

Taken together, these studies illustrate that while PS may not always manifest, its potential to influence participant responses remains substantial. This is particularly relevant in contexts where pre-tests and post-tests share identical formats, differing only in content and numerical measurements. Although the evidence does not provide definitive conclusions, it strongly indicates that PS is a plausible factor warranting careful consideration in research design and interpretation.

Research Questions

This study seeks to address two interrelated questions concerning the phenomenon of PS in science education research through two implementations conducted in different secondary schools. First, it investigates whether PS might occur in science education contexts, examining its potential influence on research outcomes. Second, it explores whether PS should be considered as another aspect while research design, something that must be considered and accounted for, whenever possible to ensure methodological rigour.

Research Design And Methods

The Solomon Four-Group Design (SFGD) received its name from Richard Lester Solomon (born in 1918, passed away in 1995) and consists of four different groups of participants, each subjected to a different experimental condition, as outlined in Table 1:

Table 1: Structure of the Solomon four-group design (Campbell & Stanley, 1966).

Groups	Assignment	Pre-test	Treatment	Post-test
Group 1 (Experimental & Pretested)	Randomly	O1	Yes	O2
Group 2 (Control & Pretested)	Randomly	O3	No	O4
Group 3 (Experimental and Non-Pretested)	Randomly		Yes	O5
Group 4 (Control and Non-Pretested)	Randomly		No	O6

The treatment in both studies was planned as five sessions focusing on getting students familiar with reason patterns related to making a fair test with variable control. These lessons were inspired by those offered within the Cognitive Acceleration through Science Education, a broadly implemented program in various countries across Europe, America, Australia, and Asia (Adey et al., 2004). The pre-test and post-test used in the studies were composed of 10 questions extracted from activities, examples, and applications from CASE program, designed to be completed within 1 hour.

Findings And Interpretation

Tables 2 and 3 present the SFGD for each study. Table 2 features a larger number of participants with a more balanced distribution across the four groups compared to Table 3. This difference arises from the availability of the study samples.

Despite the less balanced sample in the second study, normality was verified before proceeding with parametric analysis, using IBM SPSS Statistics (version 26). The Shapiro-Wilk test confirmed normality in Study 1 for both the treated group ($p = 0.469$) and the untreated group ($p = 0.240$). Similarly, in Study 2, it indicated normality for the treated group ($p = 0.496$) and the untreated group ($p = 0.254$), supporting the assumption of normality and the use of parametric methods.

Table 2. Distribution and composition of the Solomon four-group design in the 2023 Study.

Groups	Frequency	Percentage
Experimental 1	31	25 %
Control 1	23	18 %
Experimental 2	38	30 %
Control 2	34	27 %
Total	126	100 %

Table 3. Distribution and composition of the Solomon four-group design in the 2022 study.

Groups	Frequency	Percentage
Experimental 1	9	10 %
Control 1	25	29 %
Experimental 2	17	19 %
Control 2	37	42%
Total	88	100 %

To visualise the interaction between the variables, we generated Two-Way ANOVA interaction plots, which are not commonly used or shown in comparable studies. In this approach, the quantitative variable Post-test Scores were set as the dependent variable, while the two qualitative variables, Pre-test Scores and Treatment, were assigned as fixed factors. This method produced the two interaction graphs displayed below (Figures 1 & 2), illustrating the effects of pre-testing and treatment on the Post-test Scores.

Figure 1. Interaction between pre-testing and treatment on post-test scores in study 1 (2023).

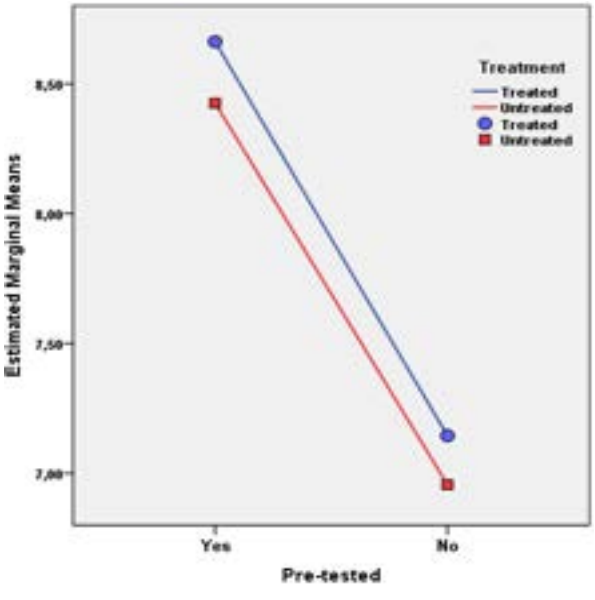
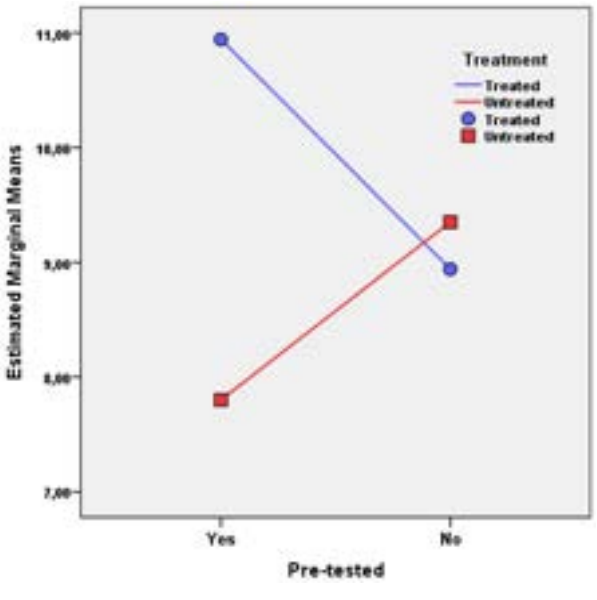


Figure 2. Interaction between pre-testing and treatment on post-test scores in study 2 (2022).



Before giving interpretation of plots, some details need to be clarified. A line in an interaction plot does not represent a mathematical function. Instead, it is a visualization of group averages calculated from a statistical model. Each line connects these averages to make trends easier to interpret. The end points of the line correspond to the estimated marginal means for each condition, providing a clear summary of the data for different groups.

Each line shows how the dependent variable (Post-test Scores) changes with the independent variable (Pre-test Scores) for a specific group (Treated or Untreated). The lines connect estimated

marginal means from the statistical model and are straight, reflecting assumed linear relationships. This simplifies group comparisons and emphasizes trends, even if real-world relationships are not strictly linear.

When lines in an interaction plot intersect, it means there is an interaction effect between variables. The effect of the treatment on the outcome depends on the condition of another variable (pre-test). Crossing lines show that the effect changes or reverses between conditions, while parallel lines indicate no interaction, meaning the effect is consistent across all conditions.

Based on these reflections, In Study 1 (Figure 1), the lines are nearly parallel (in general, no intersection), indicating that there is no interaction between pre-testing and treatment. This shows that treatment effects were consistent and unaffected by pre-testing.

In contrast, in Study 2 (Figure 2), the lines are non-parallel (in general, they intersect), indicating a significant interaction between pre-testing and treatment. This demonstrates how pre-testing influenced treatment outcomes, highlighting the variability of PS effects.

Future Directions In Adoption

By repeating the same experiment with the SFGD, we gain a broader perspective on the phenomenon of PS itself. This repetition allows us to determine whether PS consistently occurs, consistently does not occur, or varies depending on specific conditions. If the findings suggest variability, it implies that PS cannot be generalised across studies. Consequently, this variability underscores the necessity of accounting for PS in every research design to ensure methodological rigour and accurate interpretation of results.

Historically, the Pre-test-Post-test Control Group Design, now viewed as a fundamental element of the "traditional" or "usual" approach to two-group experimental studies, was once considered a prestigious and innovative methodology (Huck & McLean, 1975). Similarly, the Solomon Four-Group Design, often described as prestigious due to its ability to detect and account for PS, deserves a reassessment of its role in educational research.

It is time to recognise this design not just as a specialised tool for select studies but as an essential approach for designing and conducting experiments in education. Adopting the Solomon Design as a standard methodology could significantly enhance the precision and reliability of findings, especially in contexts where the effects of pre-testing cannot be ignored.

The absence of PS, as observed in Study 1 does not imply that researchers should revert to the usual two-group design of. Instead, it may encourage the adoption of a more rigorous approach, such as parametric analysis and meta-analysis, as proposed by Braver & Braver (1988). However, this lack of PS should not lead to a disregard for the Solomon Four-Group Design. Despite its perceived complexity, this design remains invaluable, particularly in fields like educational research, where the influence of PS should not be overlooked.

Reflections Following Conference Feedback

In light of the notes and discussion generated by attendees during the presentation of this work at the ESERA Copenhagen 2025 conference, it became clear that the topic of pre-test sensitisation (PS) continues to raise important methodological questions in science education research. The central purpose of the present article is therefore to foreground the significance, and in some contexts the practical necessity, of considering PS when designing and interpreting experimental or quasi-experimental interventions. Even when PS is not consistently observed across studies, its potential to shape participants' responses can influence the magnitude and interpretation of treatment effects. For this reason, the article argues that PS should not be treated as a marginal

issue, but rather as a plausible source of variation that warrants explicit attention whenever research conditions make it possible.

The discussion with attendees also brought out a practical question that many researchers face, which is how the analysis should proceed when a study includes a pretest, when it does not, or when it includes both conditions, as in the Solomon Four-Group Design. Put simply, attendees wanted to know what changes in the analytic strategy from one situation to another, and how to choose the most appropriate route for estimating treatment effects without drawing conclusions that the design cannot support. This ambiguity was subsequently addressed more extensively in a methodological contribution published in Review of Education (El Karkri, Quesada, & Romero-Ariza, 2025a), where the procedures and decision steps are clarified in a systematic manner, including guidance on how to proceed under the presence or absence of PS and how to select appropriate analyses for different types of outcome variables.

Attendees also commented on the uneven distribution of participants across groups in Study 2 (Table 3). The concern was not only about balance in principle, but about what such imbalance might mean for statistical power, the reliability of estimates, and the interpretation of the interaction term. Rather than treating this as a minor limitation, it was used to sharpen the methodological discussion and to explain more clearly how these issues can be handled and reported transparently. This line of critique was taken forward in a later empirical paper published in Brain Sciences (El Karkri, Quesada, & Romero-Ariza, 2025b), which examines the second study in greater depth and discusses its implications in a more detailed way. Taken together, the conference feedback and the follow-up publications help to clarify why PS deserves attention, how it can be analysed carefully, and how design-related concerns can be strengthened through systematic follow-up work. It was also suggested that Table 1 should clarify the random allocation of participants to groups. Attendees also noted that Table 1 should clarify the random allocation of participants to groups, and this has now been reflected in the revised version.

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