

**Part 3 / Strand 3**

**Science Teaching Processes And Instructional Design**

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## **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

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## 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 21<sup>st</sup>-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.

# 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 (Yáñez-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 (Yáñez-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 (Yáñez-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 (Yáñez-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 ( $\omega > 0.77$ ).

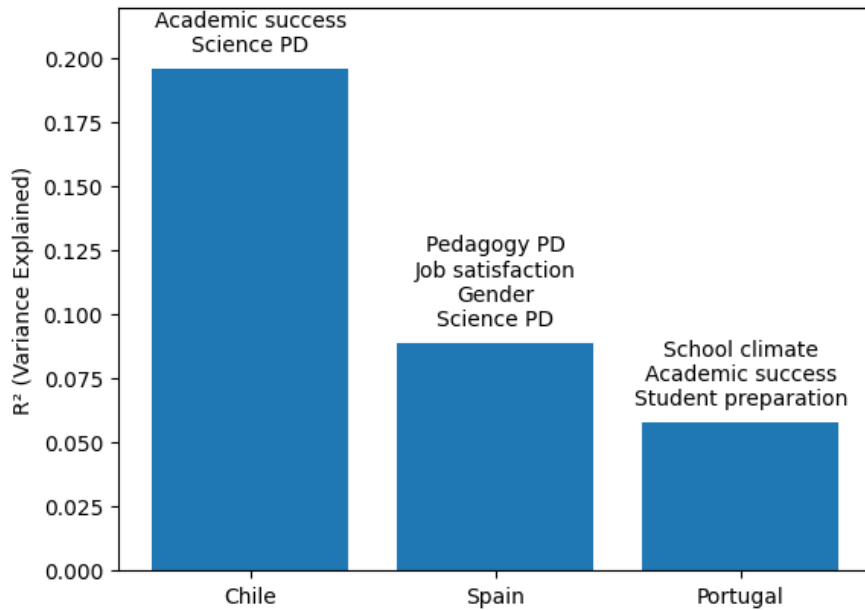
### **Data Analysis Procedure**

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 ( $R^2$ ) 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, Yáñez-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., Yáñez-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). Tokuhamma-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 Tokuhamma-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.' (Tokuhamma-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  $\text{tg}(x)$  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.

Hydrodynamika

**symbolic representation of the same physics quantity using letters**

**name of physics quantity - flow rate using words**

**using differently sized arrows to represent differences in the flow velocity**

**streamlines as a representation of the velocity of the fluid particles (based on their density)**

**different notation of flow rate using relationships between quantities**

**letters used to represent flow rate as a product of cross-sectional vector area and flow velocity**

**using bold to emphasize an importance of an idea to students**

iné a kvapalina v daného koryta musí byť množstvo pretečie ľubovoľným inaké.

Toto množstvo sa zvykne chápať dvojako:

- objemový tok  $Q_V$
- hmotnostný tok  $Q_m$

Objemový tok je Hmotnostný tok

Pozrite sa bližšie na "objemový tok": Objem kvapaliny, ktorý pretečie daným prierezom rieky za určitý čas  $t$  môžeme zistiť rýchlosťou  $v$ , teda:  $\Delta V = S \cdot v$ . Objemový tok je tento objem prečíslený časom:  $Q_V = S \cdot v$ .

Čo vyjadruje hustota prú?  $\rho = \frac{\Delta m}{\Delta V}$

Podobne môžeme zistiť hmotnostný tok:  $Q_m = \rho \cdot \Delta V = \rho \cdot S \cdot v$

Príklad:  $Q_V = \frac{\Delta V}{\Delta t}$  a  $Q_m = \frac{\Delta m}{\Delta t}$

Príklad:  $Q_m = \rho \cdot Q_V$

Vráťme sa k myšlienke, že množstvo kvapaliny, ktoré pretečie v ľubovoľnom priereze  $S$  rieky za určitý čas musí byť rovnaké. Máme na mysli objemový alebo hmotnostný tok?

### 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.

*An Outcome Of The Analysis Of The Learning Materials Using The Pillars Framework*

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.**

Vodorovným potrubím s prierezom  $300 \text{ cm}^2$  prúdi voda rýchlosťou  $2,5 \text{ m} \cdot \text{s}^{-1}$ . Tlak vody je  $150 \text{ kPa}$ .  
a) Vypočítaj, objemový tok vody.

$$Q_v = \frac{V}{\Delta t} \quad \checkmark \quad 0,150$$

$$\frac{1}{2} \rho v^2 = \frac{1}{2} \rho v^2$$

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.**

b) Vypočítaj, akou veľkou silou je kocka nadľahčovaná.

$$p_{uz} = \frac{1}{2} \rho \cdot h \cdot V = 1,25 \text{ N}$$

0b

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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## **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.

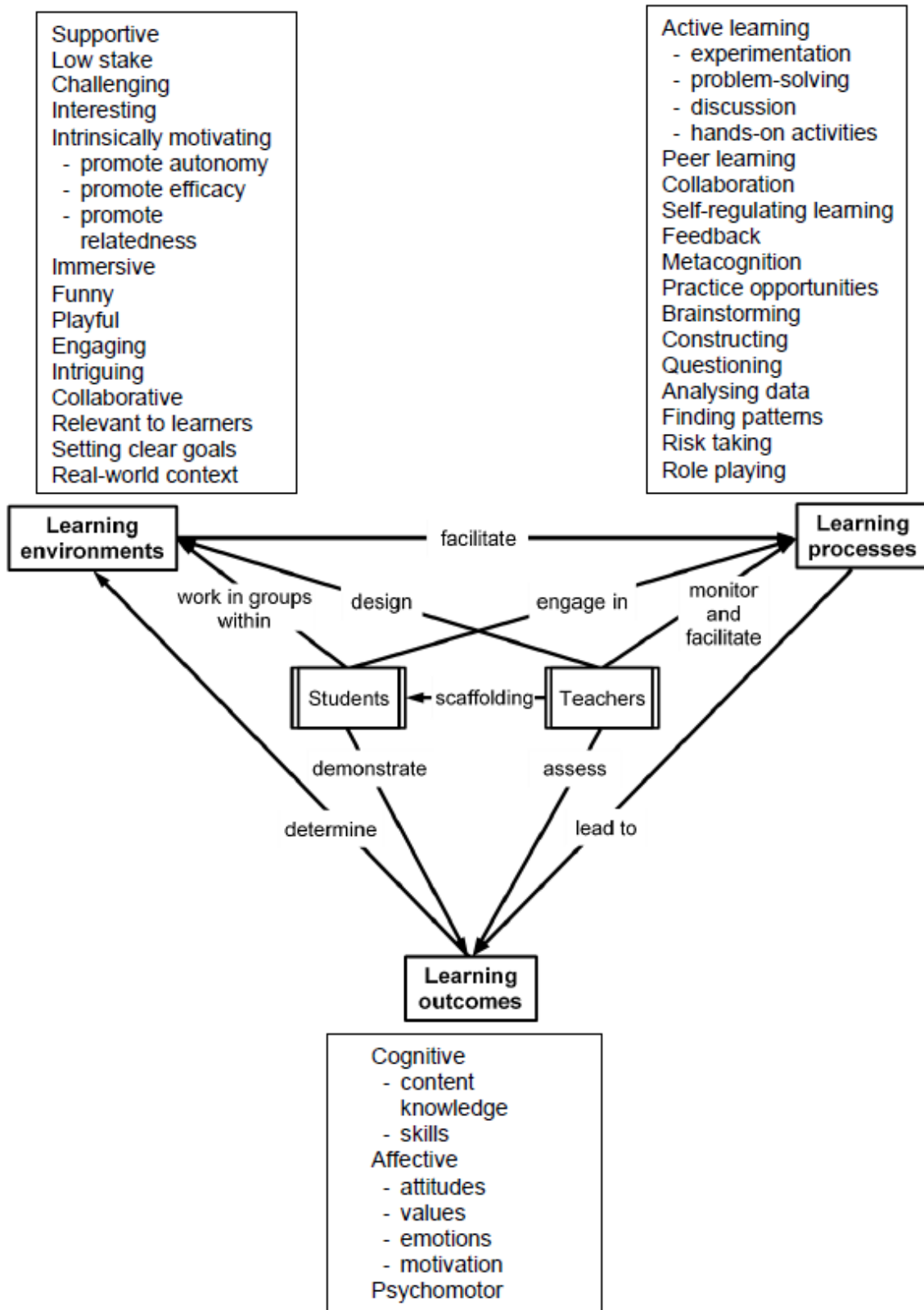
**Table 1. Theoretical underpinnings' connection to EER activities' learning mechanism**

Theoretical frameworks	Elements of effective learning
Motivational theories <ul style="list-style-type: none"> <li>• Self-Determination theory</li> <li>• Self-efficacy theory</li> <li>• Goal-setting theory</li> </ul>	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

### 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.

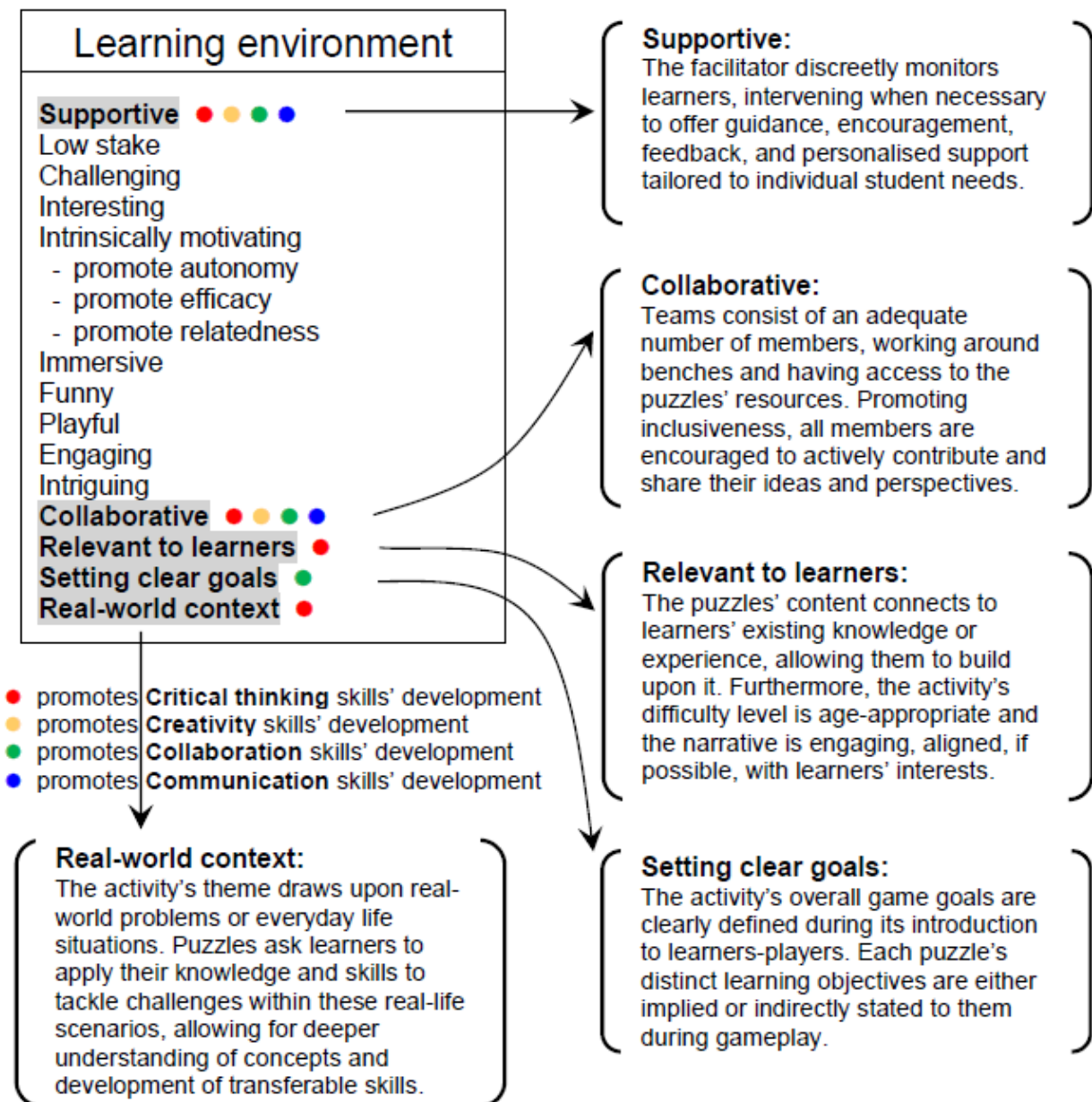
## **Analyses And Findings**

### **The Design Framework**

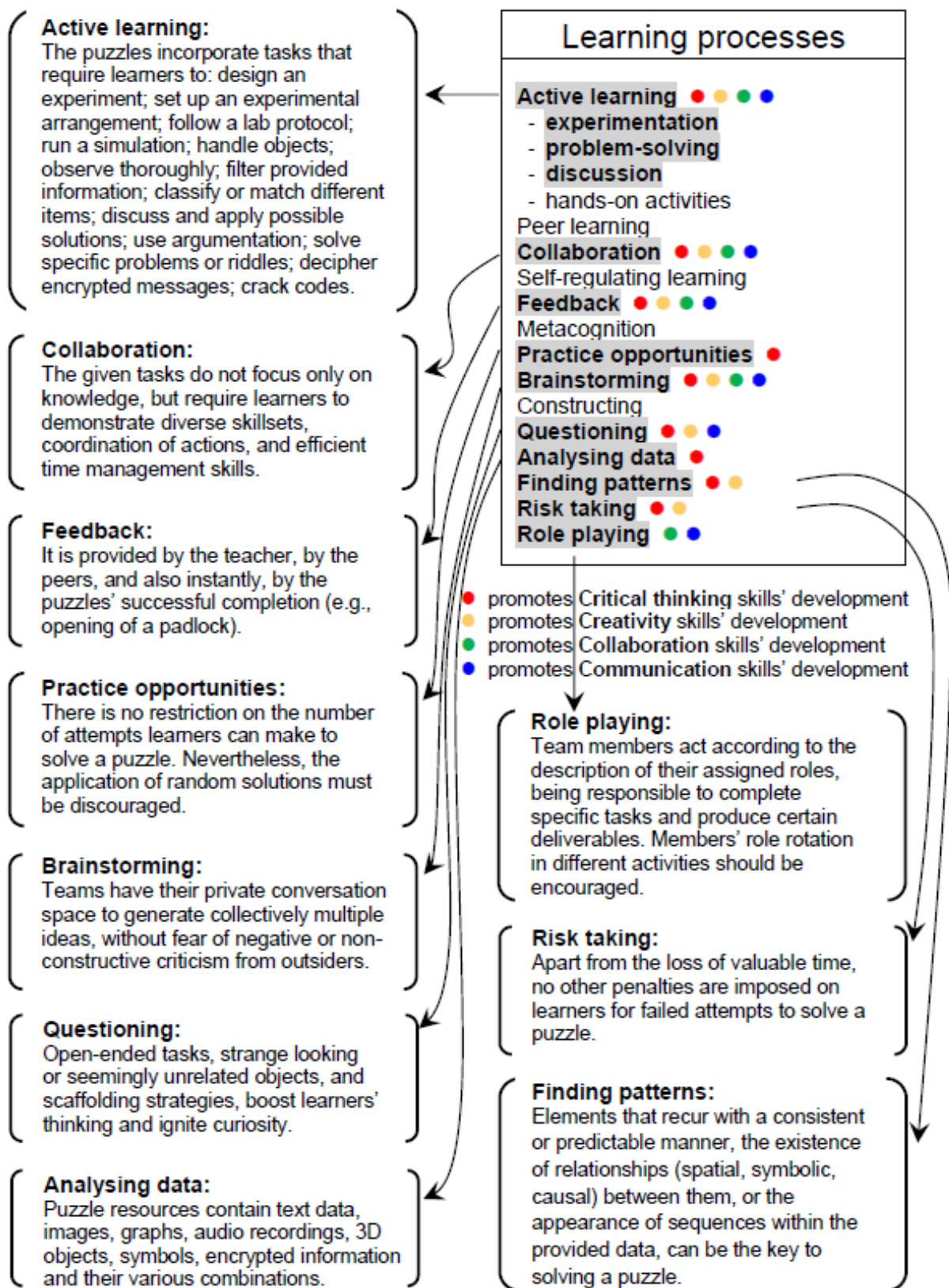
Using this model as a reference point and concentrating on its particular components that, according to the available literature, are recognized to foster the advancement of the 4C's, I devised a dedicated design framework to guide the structuring of the EER activities in this study (see Figures 2a, 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 <sup>th</sup>
2: Explicit teaching of CVS	-	5 <sup>th</sup>
3: Heat conduction in metals	CVS	3 <sup>rd</sup> , 5 <sup>th</sup> & 7 <sup>th</sup>
4: Heat conduction in solid materials	CVS	3 <sup>rd</sup> , 5 <sup>th</sup> & 7 <sup>th</sup>
5: Heat convection	Modelling	3 <sup>rd</sup> , 7 <sup>th</sup> & 8 <sup>th</sup>
6: Heat transfer by radiation	CVS	3 <sup>rd</sup> , 5 <sup>th</sup> , 7 <sup>th</sup> & 8 <sup>th</sup>

*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 3<sup>rd</sup> 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	<b>Conceptual knowledge:</b> 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 <b>Procedural knowledge:</b> understanding aspects of CVS, e.g., the ability to distinguish between valid and invalid experiments <b>Epistemological knowledge:</b> 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	-
<b>TOTAL</b>	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	-
<b>TOTAL</b>	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	-
<b>TOTAL</b>	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
<b>Level 3: Open</b>	<b>Open to student</b>	<b>Open to student</b>	<b>Open to student</b>

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 completed 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 5<sup>th</sup> grade class with 24 students visited the Lernwerkstatt.

The students frame very different questions. The questions of the 5<sup>th</sup> to 8<sup>th</sup> 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 [ $\sigma$ ]
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?”**

Categories/classes	Winter term		Summer term		Sum
	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)	
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 5<sup>th</sup> 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 4<sup>th</sup> 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:

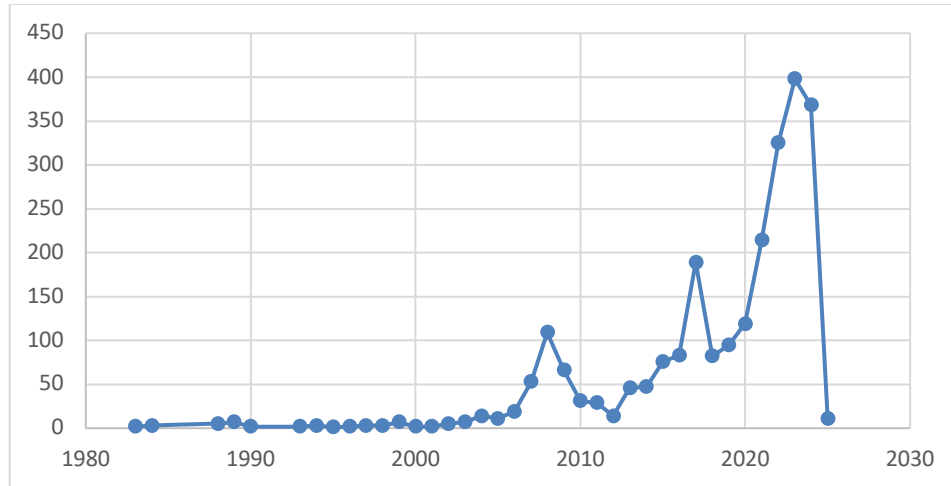
TITLE-ABS-KEY (experimentation OR experiment OR science AND education AND experiments) AND TITLE-ABS-KEY (artificial AND intelligence)

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



## 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 (Akhmadiyeva 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 (Akhmadiyeva 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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