Part1 / Strand 1

Learning Science: Conceptual Understanding

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Part 1 / Strand 1 Learning Science: Conceptual Understanding

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

Sub-themes:

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

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Strand 1: Learning Science: Conceptual Understanding

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Introduction

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

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

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

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

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

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

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

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

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

Keywords: Misconceptions, diagnostic tools, learning progression

Introduction

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

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

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

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

Methods

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

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

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

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

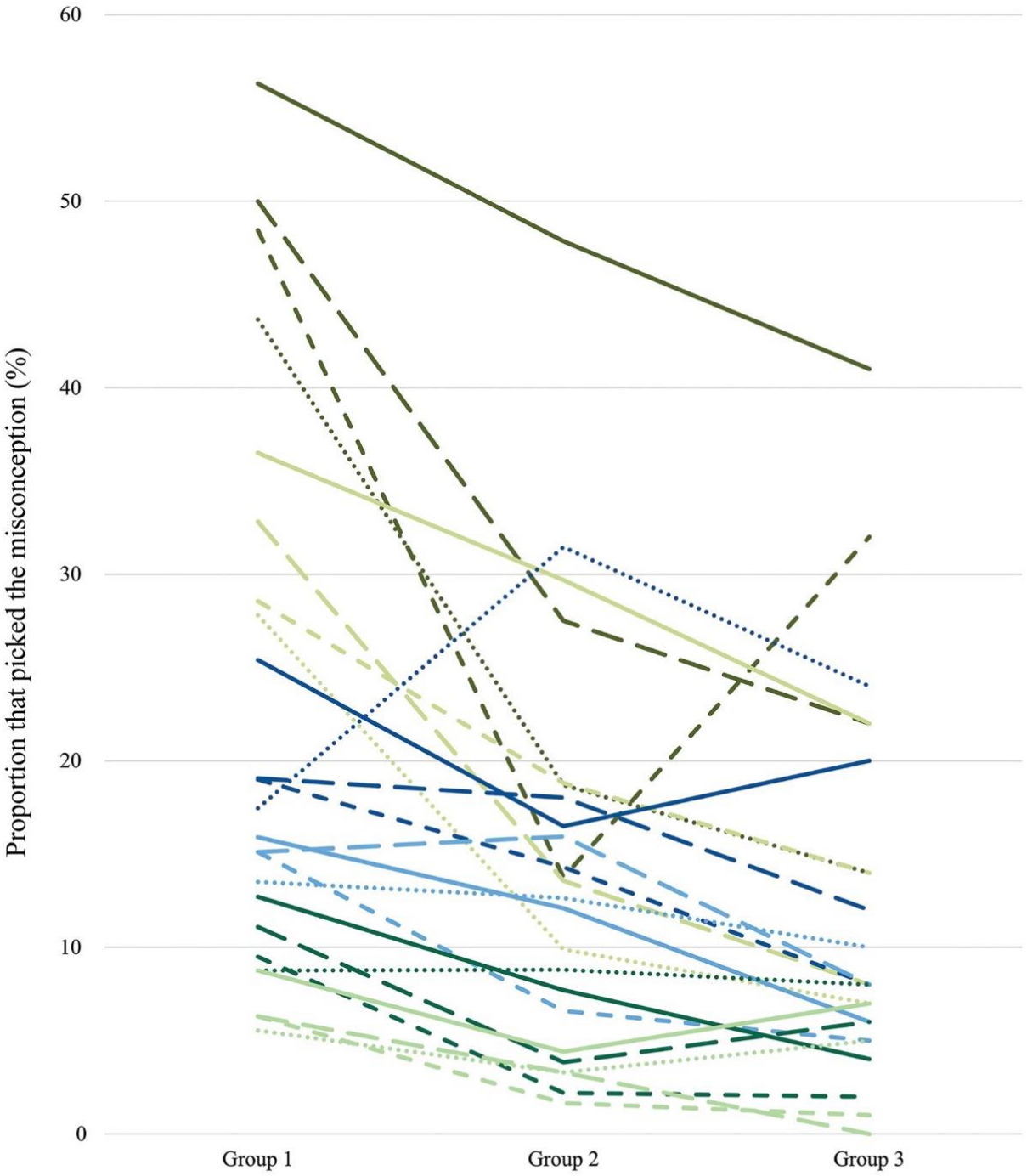
Results And Discussion

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

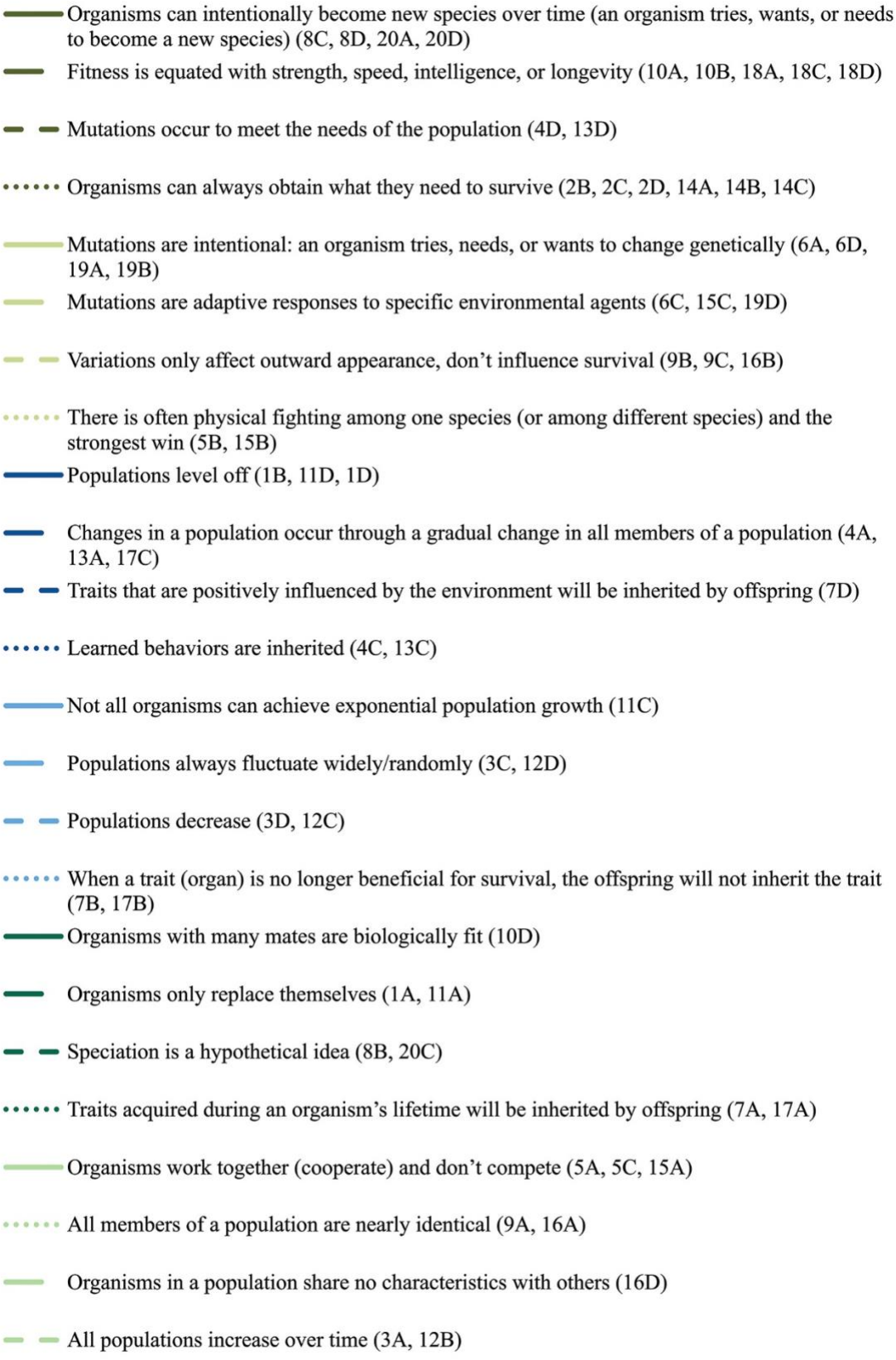
We performed a systematic search for studies that have applied CINS. Comparing all result from studies on CINS, including the results from our study, we found a general trend of lower scores reported in upper secondary school (Lucero & Petrosino, 2017) than among first-year students (Pinxten et al.,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

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

A) Line diagrams of changes in misconceptions



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



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

Relatively Rare Misconceptions

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

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

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

Misconceptions That Changed Profoundly With Biology Education

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

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

The Most Frequently Found Misconceptions

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

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

Conclusions And Further Studies

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

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

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

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

Keywords: material-embodied, optics, reasoning

Introduction

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

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

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

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

The research questions are:

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

Methods

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

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

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

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

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

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

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

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

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

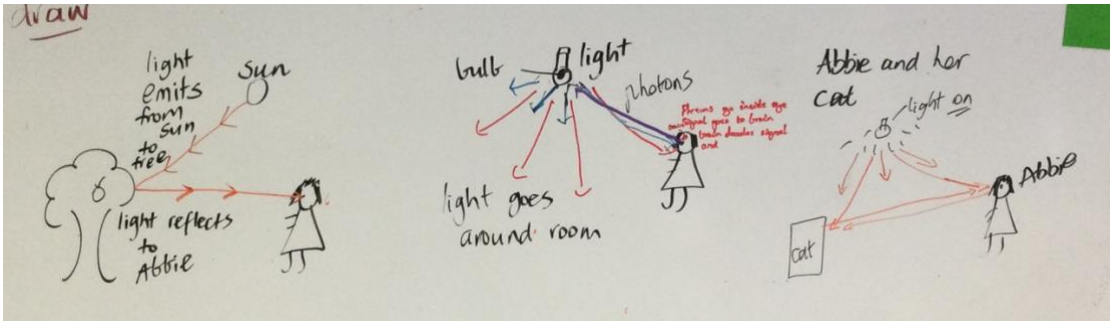
Findings

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

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

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

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



Change In Conceptions Of Vision Over The Sequence

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

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

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

The Material And Embodied Dimensions Of Understanding Light And Vision

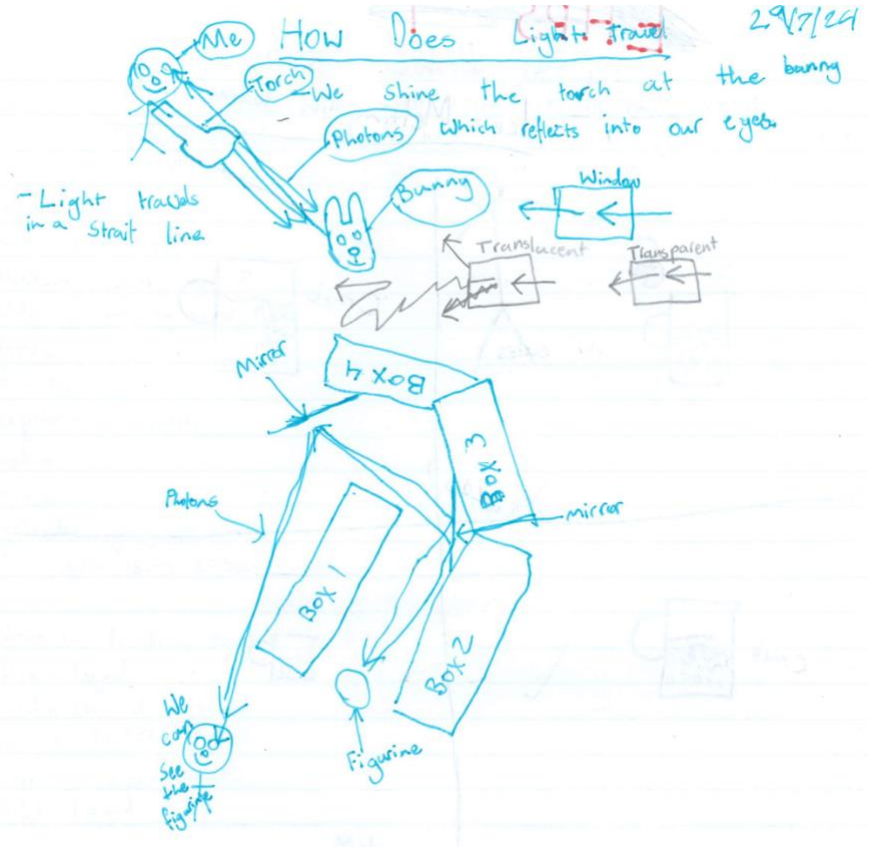
There is a clear movement of student conceptions across the sequence, particularly away from a sea of light view towards the scientific reception view of vision. The line-of-sight perspective was represented by an arrow from the eye to the object, which we interpret to reflect a focus on the active nature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

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

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

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

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



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

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

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

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

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

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

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

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

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

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

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

Discussion And Conclusion

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

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

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

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

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

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

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

Keywords: Conceptual change, cognitive ability, cognitive conflict

Introduction

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

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

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

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

Theoretical Framework

Cognitive Dissonance Theory By Festinger (1957)

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

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

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

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

Cognitive Conflict And Conceptual Change

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

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

Methods

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

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

Results

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

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

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

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

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

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

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

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

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

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

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

Discussion Of Findings

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

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

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

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

Conclusion And Recommendation

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

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

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

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

Keywords: Interleaving, Collaboration, Game-based learning

Introduction

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

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

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

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

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

Hypotheses

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

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

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

Furthermore, we assume an interaction effect:

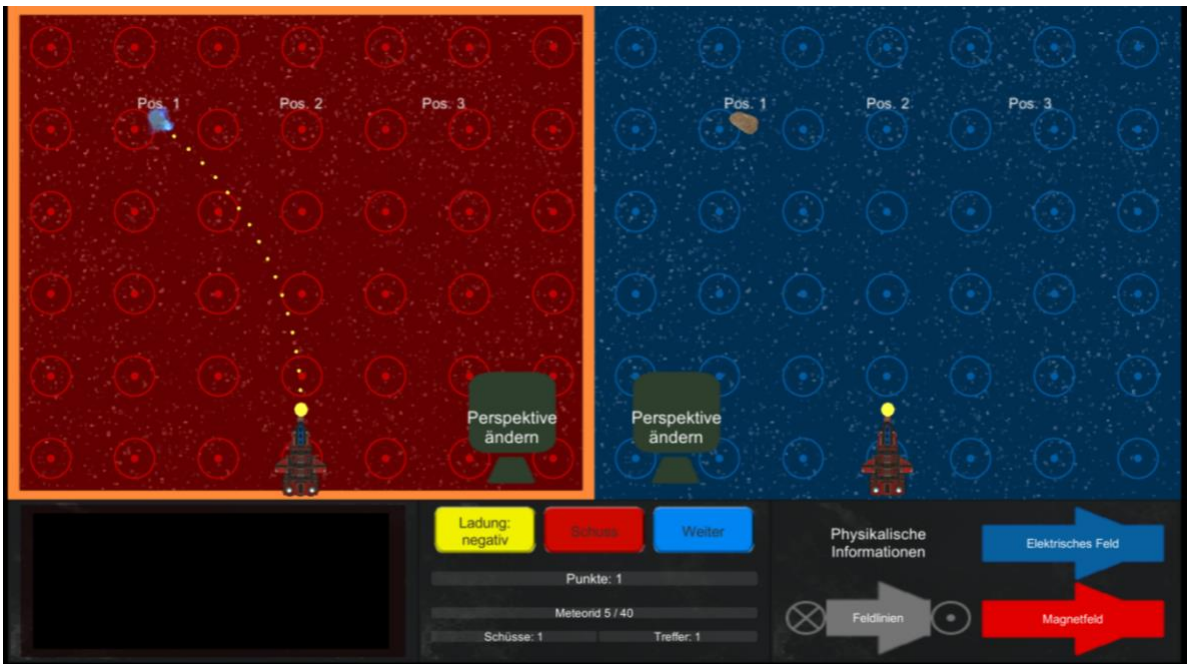
H3: The difference between students who learned collaboratively compared to students who learned individually is greater in the interleaved than in the blocked sequence a) immediately after the learning phase, as well as b) delayed after 8 weeks.

Method

Learning Environment

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

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



Participants And Experimental Design

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

Procedure

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

Dependent Variables And Scale Analysis

Academic performance

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

Self-report scales

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

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

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

Results

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

Academic Performance

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

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

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

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

Learning Experiences

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

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

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

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

Discussion

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

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

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

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

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

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

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Appendix

Self-Report Scales

Intrinsic motivation

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

Cognitive load

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

Subject interest

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

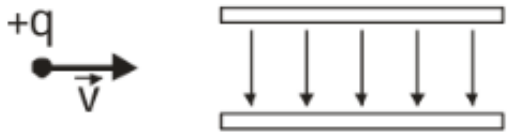
Example SPSS Syntax For The Nested Two Factorial Design

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

Example Items From The Tests

Task 3

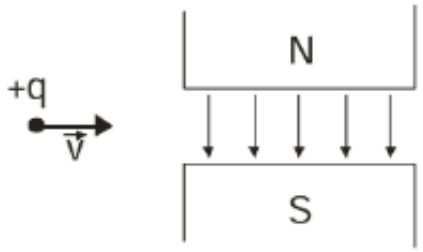
a) The figure shows a positive charge q approaching a homogeneous electric field between the plates of a capacitor at a constant speed $\vec{v}$.



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

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

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



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

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

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

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

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

Introduction

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

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

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

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

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

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

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

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

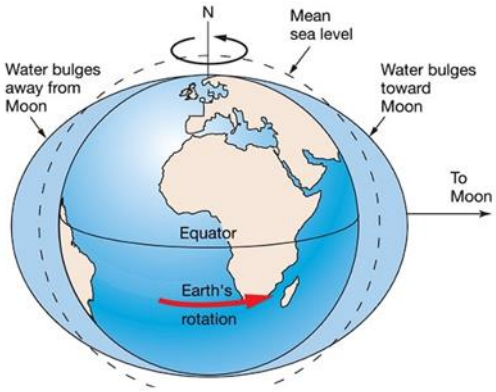
In sum, tides provide a context for connecting concepts that are often taught separately (gravity, motion, reciprocity of forces, two-body systems, barycentre) and for engaging learners through modelling to explain complex phenomena. Given the limited research base on tides within science education (Ucar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

Methodology

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

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

Figure 1. Static Tide Model.



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

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

Results

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

Table 1. Responses regarding the cause of tides.

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

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

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

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

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

Table 3. Reported characteristics of gravity.

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

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

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

Table 4. Initial responses on where gravity exists.

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

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

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

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

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

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

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

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

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

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

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

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

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

Conclusions

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

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

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

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

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

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

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

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

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

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

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

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

Keywords: Digital Resources. Higher Education. Multimodal Learning.

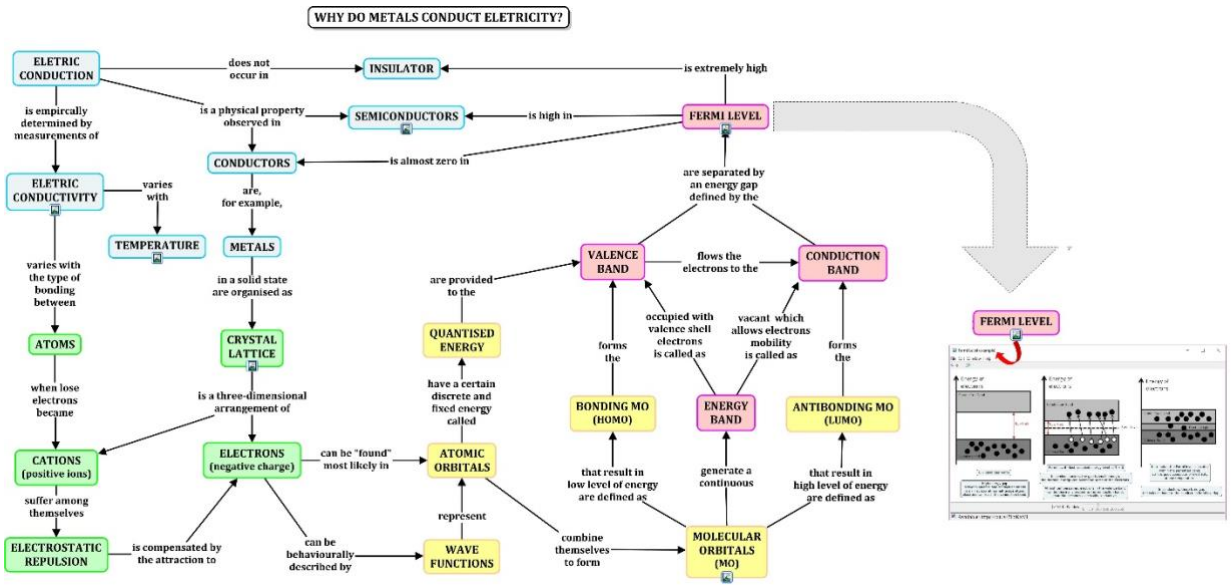
Theoretical Framework And Purpose

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

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

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

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



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

Methods

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

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

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

Results And Discussion

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

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

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

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

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

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

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

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

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

Final Remarks

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

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

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

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

Keywords: Attitudes, conceptual understanding, undergraduate learning

Introduction

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

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

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

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

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

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

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

Method

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

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

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

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

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

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

Analysis

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

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

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

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

Results

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Discussion

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Conclusion

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

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Models As Artefacts From The Perspective Of Instrumental Genesis

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

Keywords: Science models, epistemic artefacts, instrumental genesis

Introduction

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

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

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

Empirical Example: Diffusion In Cells In Upper Secondary Biology

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

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

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

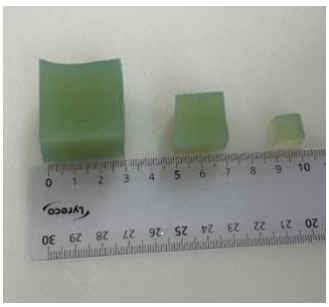


Figure 1b. The three agar blocks in vinegar.

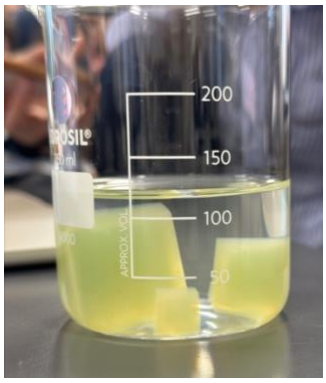
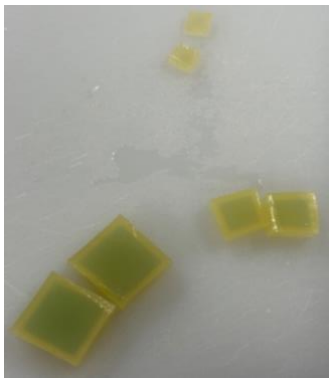


Figure 1c. The three agar blocks cut into halves after the diffusion of vinegar.



Models As Epistemic Artefacts

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

Instrumental Genesis

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

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

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

Method

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

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

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

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

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

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

Instrumental Genesis In A Biological Experiment

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

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

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

One group wrote that the experiment showed that:

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

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

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

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

Discussion

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

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

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

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

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

Introduction

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

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

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

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

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

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

Methodology

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

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

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

Results And Discussion

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Conclusion

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

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

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

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

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